Respiratory health effects of long-term exposure to different chromium species in stainless steel production

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The aim of this study was to determine whether occupational exposure to chromite, trivalent chromium (Cr^{3+}) or hexavalent chromium (Cr^{6+}) causes respiratory diseases, an excess of respiratory symptoms, a decrease in pulmonary function or signs of pneumoconiosis among workers in stainless steel production. Altogether, 203 exposed workers and 81 referents with an average employment of 23 years were investigated for indicators of respiratory health on two occasions, in 1993 and in 1998. Data collection with a self-administered questionnaire, flow volume spirometry, measurement of diffusing capacity, chest radiography and laboratory tests were carried out by a mobile research unit. Exposure to different chromium species and other metals was monitored regularly and studied separately. No adverse respiratory health effects were observed in the group exposed to Cr^{6+}, either in comparison with the control group in the first cross-sectional study or during the additional 5 year follow-up. Among the Cr^{3+} exposed people, the production of phlegm, shortness of breath and breathlessness on exertion were significantly more frequent than in the control group, but the frequency of the symptoms did not increase during the follow-up; no differences were observed in the lung function tests and the radiographic findings did not progress. In the chromite group, the prevalence of breathlessness on exertion was higher than in the control group. However, in the follow-up, the occurrence of symptoms did not differ from 1993 to 1998. In the first study, most parameters of lung function were lower among the smokers in the chromite group than among the smoking controls, but in 1998 the difference was less marked. An average exposure time of 23 years in modern ferrochromium and stainless steel production and low exposure to dusts and fumes containing Cr^{6+}, Cr^{3+}, nickel and molybdenum do not lead to respiratory changes detectable by lung function tests or radiography. The workers exposed to Cr^{3+} had more respiratory symptoms than those in the control group. The workers in the chromite mine had lower lung function test results than the control group due to earlier exposure to higher dust concentrations.

Key words: Ferrochromium production; hexavalent chromium exposure; molybdenum exposure; nickel exposure; respiratory health; stainless steel production; trivalent chromium exposure.

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Introduction

The respiratory health effects of occupational exposure to chromium compounds have been studied in several

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industries and occupations, but data on the chronic effects in stainless steel production and its different stages are limited. Chromium [1,2], chromium salts [3,4] and fumes of chromium trioxide [5] have been reported to cause asthma. Chromates, among other exposure agents in chromium plating, welding and ferrochromium production, have been connected with cases of occupational asthma [6]. Mining dust from chromite ore has been reported to cause chronic bronchitis [7]. A transient decrease in lung function has been found among chromium platers [8–10]. Increased prevalences of obstructive lung disorders were found among electrofurnace workers in a ferrochromium plant, possibly due to high levels of total dust, especially amorphous silica dust [11]. Controversial results have been reported on the risk of pneumoconiosis in chromate production [11–13]. No cases of pneumoconiosis were found among workers in a Norwegian ferrochromium plant [11].

Our previous study [14] indicated that long-term exposure to low levels of hexavalent chromium (Cr^{6+}) does not lead to any respiratory changes detectable by lung function tests or radiography, or to an increase in symptoms of respiratory disease. Among the workers exposed to trivalent chromium (Cr^{3+}), the production of phlegm, shortness of breath and breathlessness on exertion tended to appear more frequently than in the control group. The lung function test results were lower and the radiological findings were more frequent among the workers from the chromite mine than among the controls. These results were based on information from a cross-sectional study completed with information on industrial hygiene measurements of earlier exposure [14,15].

Thus, the aim of this study was to assess effects of long-term exposure to different species of chromium on the respiratory health of workers after 23 years of mean exposure. The same cohort as in the earlier study [14] was studied 5 years later. The study was also supplemented with information on exposure, including measurements of the current exposure levels to total chromium, Cr^{6+} and other air impurities in stainless steel production.

Methods

Process description

The integrated production chain of Outokumpu Oyj is unique; the mine and all stainless steel production plants are in the same region in northern Finland.

The chromite ore is mined from an open pit mine. The chromium oxide content of the ore is ~26%. After crushing, lump concentration, grinding, fine concentration and dewatering, the chromium oxide concentration rises to 42%.

In the production of ferrochrome, the fine concentrate is ground, mixed with bentonite as a binding agent, pelletized into 15 mm balls and hardened in the sintering furnace at 1400°C. Coke and quartz are added to the pellets and lump concentrate, and fed into the preheater. The heated material flows down to the arc furnace. The arc furnace is a fully closed system. In the furnace, chromite is reduced into metallic ferrochromium in the presence of carbon. Ferrochrome produced in two furnaces is tapped off at 2 h intervals. Molten ferrochrome is transported directly to the steel melting shop or cast into moulds made of finely divided ferrochrome.

In the steel melting shop, such raw materials as various types of scrap, both unalloyed and stainless, as well as alloying materials such as nickel and molybdenum, are combined with ferrochrome. These raw materials are melted in a closed arc furnace and blown with oxygen to keep the silicon content to the required level. The carbon content of the steel is lowered to the required level in an AOD (argon–oxygen decarbonization)-converter by blowing with argon and oxygen. At the end of this converting process, excess sulphur is removed with lime.

Next, in the continuous casting machine, the steel flows from the ladle via an intermediate holding basin to water-cooled copper moulds and then to a casting bow. After straightening, the slabs move to flame cutting, where they are cut to the lengths ordered.

In the next stage, the slabs are rolled in the hot rolling mill, which consists of a walking beam furnace, a roughing mill and a Steckel-type finishing mill.

On the coil build-up line of the cold rolling mill, the hot rolled strips are welded end to end to form long, uniform strips for the subsequent stages of the process. The annealing and pickling line, in which the strip is annealed to make its internal structure uniform and pickled to clean the surface, is formed by a series of units in the same line. The main parts are the gas-fired furnaces, the shot blasting units and the pickling units. Pickling is carried out electrolytically in a neutral Na_2SO_4 solution followed by mixed acid pickling (HNO_3 + HF), which ensures the cleanliness of the strip and gives it the proper stainless colour.

Cold rolling, in which the cold steel strip is reduced to its final thickness, is carried out in the Sendzimir rolling mills which operate on a backwards and forwards principle. The cold rolled strip is then lightly rolled in the skin pass mill to improve the flatness of the strip and finally split and cut to the ordered dimensions.

Subjects

All 316 workers who participated in a cross-sectional respiratory health study in 1993 [14] were invited to participate in this follow-up study. No cases of lung cancer or occupational asthma appeared among these workers during the follow-up. Two subjects who had left the company could not be contacted. Three workers had died from cardiac infarction. One subject could not be

studied because of labile hypertension. Five workers had changed production departments between 1993 and 1995: one from an exposed group to the control group, and two from the exposed groups and two from the control group to departments outside this study (transportation and construction departments). These changes were not due to health problems. There were 16 workers who did not volunteer to participate and five workers who did not show up for the examinations. Thus, altogether, 284 workers (90%) finally participated (Table 1). The subjects were divided into the same four groups as in the previous study according to exposure to different chromium compounds: Cr^{6+} (furnace department of the ferrochromium plant and the steel melting shop); Cr^{3+} (sintering and crushing departments); chromite (chromite mine); and a control group. The control group consisted of workers from the cold rolling mill (the Sendzimir rolling mill, the skin pass mill, and the splitting and cutting line), because their level of exposure to chromium or dust in general was extremely low—or non-existent.

Exposure

An exposure study was carried out throughout the entire production chain in 1987 [15]. Since then, the exposure levels have been monitored on a continuous basis. Due to technological improvements in the production processes, the exposure levels have decreased during the last decade, especially in the steel melting shop, where the highest exposure levels to Cr^{6+} were observed in 1987 (Table 2).

In the furnace department of the ferrochromium plant (Cr^{6+} group), the average dust exposure was 1.5 mg/m^3 in 1987 [15]. The dust contained an average of 5–10% chromium. The proportion of Cr^{6+} of the total chromium was 0.1–0.3%. The highest concentrations were detected during tapping in the vicinity of the tap hole, where the proportion of Cr^{6+} was 10-fold (1–3%) the level in other areas.

In the steel melting shop (Cr^{6+} group), the median exposure to total dust was 1.8 mg/m^3 (0.70 mg/m^3 in 1999). The median Cr^{6+} concentration was 0.5 mg/m^3 (0.003 mg/m^3 in 1999). The highest values among personal samples were detected in the handling of molten metal by the arc furnace (6.6 mg/m^3 in 1978 and 0.0037 in 1999). Although, judged from the stationary samples (in which the amount of air collected was large), Cr^{6+} seemed to be present at low concentrations throughout the steel smelting shop, it exceeded the detection limit of 0.5 mg/m^3 in only some of the personal samples.

The mean postshift urinary concentration of chromium was 0.02 mmol/l for the 40 workers in the steel melting shop in 1999 (0.04 mmol/l in 1987 [15] and 0.03 mmol/l in 1993 [14]). The maximum concentration was 0.07 mmol/l (0.34 mmol/l in 1987 [15] and 0.08 mmol/l in 1993 [14]).

In the sintering and crushing departments (Cr^{3+} group), the average dust exposure was 2.4 mg/m^3. At the chromite mine in Kemi (chromite group), the average dust concentration was 1 mg/m^3. The median personal exposure to chromium was 22 mg/m^3; Cr^{6+} was not detected in any of the samples.

The total dust content was low throughout the cold rolling mill (control group), averaging 0.3–0.5 mg/m^3.

Table 1. Characteristics of the study groups in 1998

Characteristic	*Cr^{6+} group (n = 104)*	*Cr^{3+} group (n = 68)*	*Chromite group (n = 31)*	*Control group (n = 81)*
Age (years)				
Mean (SD)	48.0 (6.9)	49.9 (6.6)	48.8 (7.8)	45.6 (7.0)
Range	34–64	34–65	34–67	34–68
Height (cm)				
Mean (SD)	174.4 (6.0)	174.6 (5.4)	173.5 (6.5)	173.0 (7.2)
Range	160–190	161–186	161–189	156–187
Weight (kg)				
Mean (SD)	81.4 (10.7)	82.5 (10.8)	81.2 (12.1)	81.4 (10.9)
Range	56–111	64–110	62–110	60–110
Work history (years)				
Mean (SD)	21.0 (4.2)	25.5 (4.6)	23.8 (5.5)	19.4 (2.7)
Range	13–31	14–31	14–31	13–23
Smoking status (%)				
Non-smoker	34.6	27.9	16.1	32.1
Ex-smoker	38.5	39.7	51.6	24.7
Current smoker	26.9	32.4	32.3	43.2
Present smoking (cigarettes/day)				
Mean (SD)	18.2 (11.7)	18.7 (5.4)	17.3 (3.6)	15.9 (8.5)
Total duration of smoking (years)				
Mean (SD)	18.4 (10.4)	21.9 (11.2)	23.4 (10.0)	21.9 (9.9)

Table 2. Exposure to total dust, chromium, hexavalent chromium, nickel and molybdenum in the steel melting shop

	Personal samples		*Stationary samples*	
	1987	*1999*	*1987*	*1999*
Total dust (mg/m^3)				
Median (*n*)	1.8 (153)	0.70 (12)	1.3 (63)	0.70 (34)
Maximum	18.0	2.50	7.9	3.30
Chromium (mg/m^3)				
Median (*n*)	0.0300 (82)	0.0047 (6)	0.0406 (34)	0.0053 (17)
Maximum	0.4320	0.0135	0.6030	0.0177
Hexavalent chromium (mg/m^3)				
Median (*n*)	0.0005 (72)	0.0003 (10)	0.0005 (28)	0.0030 (6)
Maximum	0.0066	0.0007	0.0037	0.0190
Nickel (mg/m^3)				
Median (*n*)	NA	0.0018 (6)	NA	0.0031 (17)
Maximum	NA	0.0094	NA	0.0300
Molybdenum (mg/m^3)				
Median (*n*)	NA	0.0003 (6)	NA	0.0006 (17)
Maximum	NA	0.0023	NA	0.0040

NA = not analysed.

In general, the content of chromium in the air in the cold rolling mill was lower than the detection limit of the measurement method.

Methods

A questionnaire was sent to the participants 1 week before the clinical examinations. It was based on the standardized questionnaire of a study carried out in the wool textile industry by the Edinburgh Study Group [16] and the definitions from the Medical Research Council (MRC) questionnaire [17] and it asked for information on personal characteristics, occupational history, respiratory symptoms, smoking habits, medication, and personal and family histories of allergic and pulmonary diseases. Some questions considered, among other things, the following items: cough, phlegm, shortness of breath and wheeze. Symptoms of rhinitis and eye irritation were also included.

Cough, lasting >3 months and improving after a holiday of >1 week, was considered to be work related. Similarly, dyspnoea occurring at least twice a month and caused or worsened by impurities in the work environment or during a work shift, but becoming better after a week's holiday, was regarded as work related. Questions about back or stomach pain and general health status were used as control questions, because they were not considered to be associated with the current occupational exposure.

Spirometry, measurement of diffusing capacity, a chest X-ray and laboratory tests were carried out by a mobile research unit with experienced laboratory technicians.

Spirometry was performed on each subject with a computerized flow volume spirometer (M905; Medikro Oy, Kuopio, Finland). Each subject was seated and wore a nose clip. At least three acceptable forced maximal expirations were performed according to the standards of the American Thoracic Society [18]. From the maximum expiratory flow volume curves, the highest forced vital capacity (FVC), forced expiratory volume in 1 s ($FEV_{1.0}$), flow rates at 50 and 25% of the vital capacity (MEF_{50}, MEF_{25}) and the mean flow (MMEF) were read. All of the values were also expressed as percentages of predicted values in Finland [19].

The spirometer was calibrated daily. Measurements were performed by two trained laboratory technicians. The technicians' performances of spirometry were compared before the study. The coefficient of variation in the FVC of the people tested was 0.74% and that of the $FEV_{1.0}$ was 1.37%.

Before the study, the M905 spirometer was compared with the M101 spirometer used in the previous study. (Both spirometers were manufactured by Medikro Oy, Kuopio, Finland.) The spirometers had a systematic difference. Results with the M905 model were slightly higher. Correction was made by reducing the 1998 FVC values by 3.7% and the $FEV_{1.0}$ values by 5.6%.

The diffusing capacity of the lungs for carbon monoxide (T_{LCO}) was measured with the Jaeger transfer test and a single-breath method. Although equipment was not the same as in the previous study, it was chosen because of the same techniques and gas concentrations. Alveolar volume (V_A) is the total lung capacity when the T_{LCO} is measured. The specific diffusion capacity is T_{LCO}/V_A. At least two satisfactory acceptable measurements were performed for each person. The mean value of the two nearest measurements was chosen [20]. The values were

adjusted to the real-time haemoglobin measurement [21]. The results were expressed as percentages of predicted values in Finland [19].

Two trained laboratory technicians examined an equal number of people. Their measurement of diffusing capacity was tested before the study. The coefficient of variation in the results of these T_{LCO} measurements was 2.65%.

Diffusing capacity is a complex phenomenon and the detailed technology of different equipment varies. Diffusing capacity values were analysed cross-sectionally in 1998. Because of a change in the diffusing capacity equipment, there was no longitudinal comparison.

In the radiographic examination, a full-size, postero-anterior chest radiograph was taken. The radiographic examinations were performed only on workers in the exposed groups, not on those in the control group. The radiographs of each exposed subject from 1993 and 1998 were classified according to the modified classification of the International Labour Office (ILO) [22]. The radiographs of each subject were examined in random order with the identification labels covered. The progression was first estimated in a side-by-side comparison of the radiographs without information on the time sequence. Then, the later radiograph was classified separately by two radiologists with experience in ILO classification. Progression was recorded if the later radiograph was estimated (in a side-by-side comparison) to have more profusion of small opacities qualitatively than the first, even if the radiographs were classified into the same profusion category.

Statistical methods

Basic statistics were used to describe the data. The frequency tables were constructed for the prevalence of symptoms for a comparison between each exposure group and the control group, and they were analysed with Fisher's exact tests. Tables were set up for the non-smokers and smokers (including ex-smokers) separately, and also for the non-smokers and smokers combined. The effect of exposure on the pulmonary functions in the cross-sectional study was analysed with Student's *t*-tests. The results of both the smokers and the non-smokers were analysed.

In the follow-up study, the changes in symptoms were divided into three groups according to whether the symptom had appeared, remained unchanged or disappeared. The differences in the symptom changes between groups were analysed with χ^2 tests for the smokers and non-smokers separately. An analysis of covariance was used when the effect of exposure on pulmonary functions was studied over the follow-up time. In the analysis, the dependent variable was the change in pulmonary function and the independent variables were study group and smoking status (as a dichotomous variable), the lung function measurement in question in 1993 being used as a covariate. Age was not taken into account in the models because the analysed lung function values were the proportions of the absolute and reference values, for which the effect of age had already been eliminated. The limit for statistical significance was set at 0.05. The computation was carried out using Statistica/Win (v. '98) software.

Results

Subjects

The participation of the workers in this follow-up study was 91% for the exposed groups and 83% for the control group.

The study groups were similar in height and weight in 1993 and 1998 (Table 1). The same applies for the age distribution of the groups, the Cr^{3+} group being the oldest (mean 49.9 years) and the control group being the youngest (mean 45.6 years). During the follow-up, there was a change in the smoking habits of the chromite-exposed group in that 58.3% were current smokers in 1993, but only 32.3% were current smokers in 1998.

Respiratory symptoms

No difference was observed in the prevalence of respiratory symptoms between the group exposed to Cr^{6+} and the referents; nor was the change during the 5 year follow-up different for these two groups (Table 3).

In 1998, the production of phlegm, shortness of breath and breathlessness on exertion were significantly more frequent in the Cr^{3+} group than in the control group when the smokers and non-smokers were combined (Tables 4 and 5). Both the smoking and non-smoking Cr^{3+} workers tended to have a higher prevalence of all three respiratory symptoms than the workers in the control group, shortness of breath being statistically significantly more frequent among the non-smoking Cr^{3+} workers (4 out of 18 subjects) than among the non-smoking controls (none among 26 subjects). The prevalence of phlegm production was also higher among the smoking Cr^{3+} workers (31%) than among the smoking controls (13%). In the follow-up, there were no differences in the changes in the occurrence of symptoms from 1993 to 1998 when the Cr^{3+} group was compared with the control group, except for the occurrence of rhinitis, which was observed to decrease significantly more ($P = 0.01$) among the non-smoking Cr^{3+} workers than among the non-smoking controls.

The prevalence of breathlessness on exertion tended to be higher in the chromite group than in the control group ($P = 0.07$). The change in the prevalence of any symptom over time did not differ between the chromite group and the controls.

Table 3. Differences in percentages [with 95% confidence intervals (CI)] within exposure groups in 1993 and 1998, and differences in percentages (with 95% CI) between the exposure groups and the control group in 1998

	Cr^{6+} group (n = 104)		*Cr^{3+} group (n = 68)*		*Chromite group (n = 31)*		*Control group (n = 81)*
Symptoms	*Difference within group (CI)*	*Difference between group and control (CI)*	*Difference within group (CI)*	*Difference between group and control (CI)*	*Difference within group (CI)*	*Difference between group and control (CI)*	*Difference within group (CI)*
Cough >3/12 months	1.9 (–6.5–10.3)	–1.1 (–10.3–8.1)	7.3 (–5.8–20.4)	3.3 (–8.0–14.6)	–1.4 (–18.9–16.1)	4.0 (–10.8–18.8)	–1.7 (–11.2–7.8)
Work-related cough	3.9 (–1.3–9.1)	–0.6 (–4.9–3.7)	4.4 (–4.7–13.5)	3.4 (–3.2–10.0)	–3.3 (–14.0–7.4)	4.0 (–5.3–13.3)	–1.3 (–5.4–2.8)
Phlegm >3/12 months	7.7 (–1.5–16.9)	–1.5 (–10.4–7.4)	0.0 (–15.1–15.1)	16.8 (4.1–29.5)	6.5 (–13.1–26.1)	5.0 (–9.6–19.6)	–3.7 (–12.6–5.2)
Shortness of breath (and wheezing)	2.9 (–3.7–9.5)	1.0 (–4.9–6.9)	–1.7 (–14.4–11.0)	14.1 (4.0–24.2)	6.0 (–9.0–21.0)	3.1 (–7.0–13.2)	2.4 (–4.3–9.1)
Breathlessness on exertion[a]	–0.9 (–9.4–7.6)	5.2 (–2.9–13.3)	–1.7 (–14.8–11.4)	13.1 (2.2–24.0)	–6.5 (–24.7–11.7)	13.1 (–1.8–28.0)	–1.4 (–8.5–5.7)
Rhinitis >3/12 months	–7.7 (–20.1–4.7)	0.4 (–13.3–14.1)	19.2 (3.2–35.2)	–5.4 (–20.2–9.4)	–3.3 (–26.2–19.6)	–1.0 (–20.4–18.4)	–8.6 (–22.5–5.3)
Eye symptoms >3/12 months	–0.9 (–11.5–9.7)	5.6 (–5.0–16.2)	3.0 (–8.9–14.9)	–0.4 (–11.4–10.6)	–25.8 (–42.9—8.7)	15.4 (–2.2–33.0)	–2.5 (–12.6–7.6)

[a]Shortness of breath when hurrying on level ground.

Table 4. Prevalence (%) of respiratory symptoms in non-smokers

	Cr^{6+} group (n = 41)		*Cr^{3+} group (n = 21)*		*Chromite group (n = 5)*		*Control group (n = 27)*	
Symptoms	*1993*	*1998*	*1993*	*1998*	*1993*	*1998*	*1993*	*1998*
Cough >3/12 months	12.8	8.1	9.5	0.0	0.0	0.0	3.7	8.3
Work-related cough	7.3	0.0	9.5	0.0	0.0	0.0	3.7	3.7
Phlegm >3/12 months	14.6	4.9	23.8	19.1	0.0	0.0	3.7	7.4
Shortness of breath (and wheezing)	2.4	7.3	9.5	20.0*	20.0	0.0	3.7	0.0
Breathlessness on exertion[a]	9.8	9.8	4.8	14.3	0.0	0.0	0.0	3.7
Rhinitis >3/12 months	26.8	36.6	57.1	28.6	0.0	0.0	18.5	29.6
Eye symptoms >3/12 months	29.3	24.4	14.3	19.1	0.0	20.0	7.4	14.8

[a]Shortness of breath when hurrying on level ground.

*$P < 0.05$, exposure group versus control group in Fisher's exact test (differences in 1993 not analysed).

Table 5. Prevalence (%) of respiratory symptoms in smokers (current and former)

	Cr^{6+} group (n = 63)		*Cr^{3+} group (n = 47)*		*Chromite group (n = 26)*		*Control group (n = 52)*	
Symptoms	*1993*	*1998*	*1993*	*1998*	*1993*	*1998*	*1993*	*1998*
Cough >3/12 months	10.0	9.8	26.1	19.1	15.4	17.4	11.5	11.9
Work-related cough	4.8	3.2	10.6	8.5	3.9	7.7	0.0	1.9
Phlegm >3/12 months	19.1	12.7	29.8	31.9*	26.9	19.2	9.6	13.5
Shortness of breath (and wheezing)	11.1	3.2	19.2	17.0	11.5	8.0	7.7	5.9
Breathlessness on exertion[a]	11.1	12.7	23.4	21.7	15.4	23.1	7.7	8.0
Rhinitis >3/12 months	25.4	31.8	42.6	27.7	34.6	38.5	26.9	36.5
Eye symptoms >3/12 months	11.1	15.9	17.0	10.6	3.9	30.8	13.5	13.5

[a]Shortness of breath when hurrying on level ground.

*$P < 0.05$, exposure group versus control group in Fisher's exact test (differences in 1993 not analysed).

Lung function tests

Among the smokers (including ex-smokers) and the non-smokers, no exposure-related deterioration in lung function was observed in the group exposed to Cr^{6+}, or in the group exposed to Cr^{3+} and the controls, nor did the change during the 5 year follow-up differ for these groups. In general, the smokers had lower lung function test results (Tables 6 and 7). The diffusing capacity and specific diffusing capacity were significantly higher among the smokers in the Cr^{6+} group than among the smoking controls.

Among the smokers in the chromite group, FVC was significantly lower ($P = 0.03$) than among the smoking controls in the cross-sectional comparison in 1998. No differences in $FEV_{1.0}$, MEF_{50}, MEF_{25}, MMEF or peak expiratory flow (PEF) were seen in the comparison between each exposed group and the control group.

Because of the small number of non-smoking workers in the chromite group, their results could not be analysed separately. When the smokers and non-smokers in the chromite group were combined and the group was compared as a whole, no significant differences between the exposed workers and the controls were observed for any of the lung function variables. In the follow-up study, $FEV_{1.0}$ decreased less in the chromite group than in the control group.

Radiographs

In the comparison of the radiographs from 1998 with those from 1993, the profusion of small opacities had progressed in three people and the profusion category for these workers was ≥1/0. One of these workers was exposed to Cr^{6+}, one belonged to the chromite group and one was exposed to Cr^{3+}.

Discussion

The aim of both studies (the cross-sectional in 1993 and follow-up in 1998) focused on assessing the long-term respiratory effects of exposure to different chromium compounds in the production chain of stainless steel. The

Table 6. Lung function measurements [mean (SD)] as a percentage of predicted values (non-smokers)

Lung function variable	*Cr^{6+} group (n = 41)*		*Cr^{3+} group (n = 21)*		*Chromite group (n = 5)*		*Control group (n = 27)*	
	1993	*1998*	*1993*	*1998*	*1993*	*1998*	*1993*	*1998*
FVC	96.4 (11.1)	94.2 (12.0)	93.4 (9.1)	93.6 (11.0)	96.1 (11.1)	97.0 (12.3)	93.4 (9.7)	92.4 (8.5)
$FEV_{1.0}$	95.5 (11.4)	91.9 (11.3)	92.9 (11.2)	91.2 (12.9)	94.2 (10.8)	94.3 (13.2)	94.7 (11.6)	92.3 (10.5)
FEV%	99.8 (6.6)	97.9 (7.2)	99.1 (6.7)	97.2 (7.4)	97.7 (6.6)	97.4 (8.4)	101.5 (5.8)	99.8 (5.8)
TLCO	104.8 (11.8)	112.1 (13.9)	107.8 (15.8)	115.5 (16.9)	105.6 (5.9)	109.7 (4.8)	106.6 (14.7)	112.1 (11.7)
TLCOHb	104.1 (11.9)	109.2 (13.9)	107.8 (14.7)	110.6 (19.4)	105.9 (5.3)	106.1 (3.4)	106.3 (13.9)	107.4 (13.1)
TLCO/VA	108.6 (16.7)	109.9 (14.4)	113.2 (17.3)	112.0 (15.8)	111.4 (21.3)	104.0 (12.7)	111.5 (18.2)	110.9 (13.9)
TLCO/VAHb	108.0 (16.7)	107.2 (13.4)	113.3 (15.9)	107.1 (17.2)	111.4 (19.4)	101.0 (13.5)	111.4 (18.1)	106.0 (13.8)

Abbreviations: FVC = forced vital capacity; $FEV_{1.0}$ = forced expiratory volume in 1 s; FEV% = $FEV_{1.0}$/FVC × 100; TLCO = diffusing capacity; TLCOHb = diffusing capacity adjusted for haemoglobin; TLCO/VA = specific diffusing capacity; TLCO/VAHb = specific diffusing capacity adjusted for haemoglobin.

Table 7. Lung function measurements [mean (SD)] as a percentage of predicted values (smokers[a])

Lung function variable	*Cr^{6+} group (n = 63)*		*Cr^{3+} group (n = 47)*		*Chromite group (n = 26)*		*Control group (n = 52)*	
	1993	*1998*	*1993*	*1998*	*1993*	*1998*	*1993*	*1998*
FVC	93.5 (9.6)	89.6 (11.5)	90.7 (9.6)	90.3 (10.6)	87.8 (10.9)	87.2* (10.3)	94.9 (10.8)	92.9 (11.5)
$FEV_{1.0}$	91.8 (12.5)	87.9 (14.1)	89.1 (10.7)	87.6 (12.2)	85.1 (13.0)	83.0 (12.4)	92.6 (12.3)	88.5 (13.6)
FEV%	98.2 (8.0)	97.8 (7.8)	98.0 (7.1)	97.1 (7.8)	94.4 (8.1)	95.2 (8.4)	97.4 (7.2)	95.2 (8.7)
TLCO	98.5 (16.6)	109.0* (17.5)	92.4 (12.8)	102.9 (14.9)	93.1 (13.9)	100.3 (15.7)	94.9 (13.1)	102.1 (11.8)
TLCOHb	97.5 (15.5)	103.8* (16.6)	92.5 (12.6)	96.2 (14.6)	92.9 (13.7)	92.9 (16.3)	94.6 (13.6)	95.9 (11.8)
TLCO/VA	104.9 (16.56)	92.1* (13.0)	98.9 (15.9)	87.3 (14.1)	103.8 (15.9)	90.0 (16.4)	99.9 (14.6)	86.3 (10.8)
TLCO/VAHb	104.7 (16.4)	101.9* (14.4)	99.2 (15.9)	94.8 (16.1)	103.8 (16.3)	96.9 (19.6)	99.8 (15.2)	94.1 (12.5)

For abbreviations, see Table 6.

[a]Smokers include both current and ex-smokers.

*$P < 0.05$. Cr^{6+}, Cr^{3+} and chromite groups versus the control group (differences in 1993 not analysed).

results of this follow-up study did not differ from those of our previous cross-sectional study 5 years earlier. Because the cross-sectional study design always involves risk of selection bias, we wanted to complete it with this follow-up in order to gather more accurate information on the risks for respiratory disorders. Even with the follow-up, it was not possible to remove the effect of potential bias developing from earlier time periods of exposure. It was, however, possible to demonstrate possible current effects of exposure to different chromium compounds on the respiratory system, if they exist. The group sizes were fairly small, especially the one from the chromite mine. All the workers meeting the inclusion criteria were, however, examined. Therefore, from the point of view of occupational health care, the follow-up increased the power in assessing risks for this population. The duration of employment in the exposed groups was sufficiently long for this purpose, the mean exposure period varying from 21 to 26 years. As with the majority of the labour force in general, all the workers in this study had been employed by the same production departments throughout their careers and their occupational exposure has been regularly monitored, which is an advantage for this kind of study design.

The control group was originally chosen from the same company, which ensured a similar socio-economic background and similar employment criteria for the groups. The alternative choice for a control group would have been controversial, in that a small town does not offer many workplaces with the same characteristics as the study population and most 'blue collar' workers have notable exposures to other pollutants that may disturb the comparison of exposed and 'unexposed' groups. Even clerical controls may have entered office work because of allergies and other selective health reasons. Although our controls were exposed to minor amounts of air pollutants in their work environment, it is very likely, according to accurate exposure measurements, that their exposure was not able to induce chronic respiratory effects. The follow-up study concentrated on comparing the change or stability of the differences in the variables between different groups with different exposure and, therefore, the long-term effects should have been apparent in this comparison, if such effects existed.

The participation rate was high. Altogether, 90% of those studied in 1993 participated in the follow-up study. The rate for the workers able and eligible to participate was, however, even higher, at 95%.

The health history of the former workers and the reasons for leaving the company were assessed by a questionnaire in 1993, and by personal inquiry and information from the medical records of the company in 1998. Thus, survivor bias can be regarded as small in this study.

We assessed the results (1993) of people who did not participate in the follow-up in 1998 (n = 32). For those from the Cr^{6+}, Cr^{3+} and control groups, there was a similar distribution of symptoms and mean lung function values. However, in the chromite group, three people had lung functions below the predicted values. This finding had to be taken into account in the interpretation of the results of the chromite group because of the small number of workers in that group.

According to biological monitoring, and stationary and personal exposure measurements, occupational exposure to chromium has been decreasing at the plant since the 1980s. The exposure levels of other alloying metals, such as nickel and molybdenum, are also low.

In a field emission scanning electron microscope analysis, the aerosols from the ferrochromium smelter were observed to contain agglomerates of particles with a diameter <1 mm [23]. Chromium seemed to be dissolved in a silica matrix. Most particles were covered with a thin layer of zinc oxide. The particles in the aerosols encountered in the steel melting shop were predominantly metal alloys. No pure chromium or nickel particles were observed. The particles had an iron oxide or iron core surrounded by chromium and nickel as alloys and silicates and oxides. These complexes are chemically tightly bound and insoluble in a biological environment.

The low level of metal fumes and the surface structure of the metal aerosols encountered in the workplace air in the ferrochromium smelter and the stainless steel melting shop may partly explain the scarcity of new respiratory findings.

Rather than being directed towards finding new cases of asthma or other diseases, the methods of our study were directed towards the early detection of worsening respiratory health (symptoms or subclinical lung function changes or radiological findings). The occupational health care unit of the company was able to collect data on diseases comprehensively at the individual level. No new cases of asthma, cancer or pneumoconiosis were found in 1993–1998.

The prevalences of symptoms were similar in 1993 and 1998. The workers in the Cr^{3+} group still had more symptoms (production of phlegm, shortness of breath and breathlessness on exertion) than the workers in the control group. The difference was significant in the group comparison in both years, without stratification or analysis according to known confounders. In 1993, the logistic regression analysis adjusted with confounders showed no difference in these prevalences between these groups. Therefore, because of the small number of observations, it was best to consider changes in the occurrence of symptoms and a group comparison, as we have described in the Statistical methods section. It showed that this excess of symptoms in the Cr^{3+} group was not related to smoking habits. The increased prevalence of the pattern of symptoms in the Cr^{3+} group seemed to be consistent in that

it was also observed in 1993. Because there were no differences in the deterioration of lung functions between the Cr^{3+} group and the control group, this observation of respiratory symptoms does not indicate the parallel development of chronic obstructive pulmonary disease (COPD). The reason for this observation of excess of respiratory symptoms may be irritation, but the occupational exposure pattern does not lead to any evident explanation.

The $FEV_{1.0}$ decreased significantly less in the chromite group than in the control group. Other lung function variables also had the same tendency. The lung functions were, or tended to be, lower in the chromite group than in the control group both in 1993 and in 1998. However, the analysis of the changes in lung function was adjusted for the initial lung function value (as covariate) and therefore the lower starting point did not explain this result concerning change. The relative improvement of the lung function test in the chromite-exposed group was probably related to the decrease in smoking. The number of ex-smokers had doubled between 1993 and 1998 and, in the analysis, smokers and ex-smokers were not separated. However, it is likely that the causative agent behind the lower lung function tests in this group, also observed in 1993, is the exposure more than two decades ago to higher dust concentrations, including fibrous components [14].

The stability of the radiological findings indicates that the recent exposure levels to potentially fibrogenic dusts have been low. Radiological parenchymal findings according to the ILO classification were not common in a previous study [14]. Based on our radiological findings in two studies, it seems evident that exposure to chromium compounds at the levels described does not produce fibrosis. Selection bias is not an explanation for this observation, because it is unlikely that symptomless mild fibrosis would cause selection among exposed workers.

In conclusion, an average exposure time of 23 years in modern ferrochromium and stainless steel production with low exposure to dusts and fumes containing hexavalent and trivalent chromium, nickel and molybdenum does not lead to respiratory changes detectable by lung function tests or radiography. A slight increase in respiratory symptoms without deterioration of lung function was observed among the workers exposed to Cr^{3+}. The workers at the chromite mine had lower lung function test results than the control group, probably because of earlier exposure to higher dust concentrations.

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