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Risk assessment of silicosis and lung cancer among construction workers exposed to respirable quartz

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Objectives The aim of this study was to assess the magnitude of the silicosis and cancer risk among construction workers.

Methods In 1998, 1335 of 4173 invited construction workers with expected high cumulative exposure to quartz were studied for early signs of silicosis. In 2002 the study was repeated for 96 persons. Exposure measurements were performed among 34 construction workers. Silicosis risk was assessed by converting study results to the whole group of construction workers and by risk analysis based on exposure data combined with documented exposure response relations. Excess risk for cancer was also calculated from available exposure measures.

Results The initial study among construction workers revealed a prevalence of 0.8% of workers with rounded opacities on chest X-rays. The follow-up showed a much higher percentage (12%) of persons with rounded opacities on X-rays. The results were confirmed by high-resolution computed tomography. It was estimated that roughly 9% of the population initially studied (N=1335) would have been observed with rounded opacities at follow-up. On the basis of the exposure data, a lifetime risk of silicosis above 5% is expected for workers exposed to levels above the occupational exposure limits. An excess lifetime risk for lung cancer is expected when workers are exposed to quartz levels above the occupational exposure limit. Due to the scarcity of exposure data, an estimation of the size of the group at risk is not yet possible.

Conclusions All available data indicate that construction workers exposed to quartz levels above occupational exposure limits are clearly at elevated risk of silicosis and other respiratory diseases.

Key terms construction industry; lung cancer; quartz exposure; risk assessment; silica; silicosis.

The incidence rates of silicosis have decreased over the last few decades (1–3); however, the estimated 3600 to 7300 new cases of silicosis per year in the United States between 1987 and 1996 (4) shows that adequate control of exposure to respirable quartz dust has not yet been achieved. The construction industry is one of the trades in which quartz (crystalline silica) exposure levels still frequently exceed the occupational exposure limit (OEL) (5–17). As a consequence, silicosis is still being diagnosed among construction workers (18, 19) and is also reported as a cause of death in this occupational group (20–22). Chronic silicosis is a slowly progressive disorder that is characterized by multiple fibrotic nodules in the lung parenchyma and results in impaired lung function, right-sided heart failure, increased susceptibility to certain infections such as tuberculosis, and premature death (23). Radiological changes occur after ≥10 years from first exposure, involving nodular lesions (bilateral, multiple, rounded opacities) often more prominent in the upper lobes. In the first stage of silicosis, nodules are usually small (≤1 cm). Many manmade construction materials, such as bricks and concrete, can contain high levels of α-quartz. Due to increasing specialization in construction work and the increase in the use of powered handheld tools, some workers may experience extremely high exposures over complete workdays. In 1990 Brendstrup et al (24) predicted that the peak in silicosis cases from construction activities lies in the future, not the past. It took until the 1990s, in the years of the preparation of the new classification in 1997 for crystalline silica as a carcinogen in humans by the International Agency for Research on Cancer (IARC) (25), to increase the awareness of the risk of silicosis among construction workers. The magnitude of the

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risk of silicosis among construction workers is unknown. The aim of the analysis in this paper was to estimate the risk of silicosis among construction workers that are regularly exposed to quartz dust. Data from a case–control study among construction workers was combined with results from a larger cross-sectional study of 4.5 years earlier. A risk assessment was also performed for silicosis and lung cancer on the basis of exposure data in relation to health effects among other populations. Translating the calculated figures to the whole construction worker population is complicated, however, as construction workers cannot be considered a homogeneous exposure group (9) and selection bias influenced the results.

Table 1. Potential exposure to quartz-containing dust in the construction worker subgroups.

Job title	Exposure index [a]	Number of workers (estimate)	Quartz exposure (frequency) [b]	Quartz exposure (level) [c]	Dust exposure (level) [c]
Concrete driller	0.6	400	++	+	+
Steel bender		3 500	–	–	–
Concrete worker	0.4	3 000	–	–	–
Concrete blasting worker	0.5	100 [d]	++	++	++
Gypsum brick layer	0.2	3 500	++	–	++
Drain workers		500	~	+	–
Glazier		?	~	–	–
Piler		1 000	–	–	–
Pipe fitter		500 ?	?	+?	–?
Bricklayer or mason (new houses)	0.3	30 000	~	–	+
Bricklayer's assistant	0.3	13 525	~	–	+
Roofer (tiles)		500 ?	+	+?	+
Installers of ceilings	0.2	100 [d]	+	+/++	++
Sewage system workers		4 000	~	–	–
Recess miller	1	200?	++	++	++
Demolition worker	1	2 400	+/++	++	++
Plasterer–spack		?	+	+	++
Railway construction workers	0.4	2 000	~	–	?
Insulation worker (walls)	0.2	500	+	–/+	+
Sheetpiling builder		150	–	–	–
Scaffolding builder		2 000	–	–	–
Plasterer	0.3	6 000	+	–	++
Tiler	0.2	3 500	~	+?	–
Carpenter for maintenance and renovation	0.2	80 000	~/+	+	+
Carpenter (framing)		15 000	–	–	–
Floorer	0.3	1 600	++	–/+	++
Tuck pointer	0.2	2 500	++	++	++
Road construction worker	0.4	2 000	~	+	+
Road marker		300	–	–	+
Total		178 575			

[a] Qualitative measure of quartz exposure, ranging from 0 to 1.
[b] – almost never (less than once a week), ~ incidently (~ once a week), + regularly (~ once a day), ++ frequently (more than once a day).
[c] – low (lower than the occupational exposure limit), + moderate (~ occupational exposure limit), ++ high (higher than the occupational exposure limit).
[d] Estimation, because group size was unknown.

Study population and methods

Using data from a cross-sectional study on silicosis among 1335 construction workers and a follow-up on 96 of these workers, we assessed the risk of silicosis. The risk of silicosis and lung cancer was also assessed on the basis of exposure among construction workers in relation to exposure–response associations in other occupational groups, such as miners.

Population at risk

In The Netherlands, with a population of 16 000 000, almost 300 000 people work in the construction trade. The total number of workers at risk for exposure to quartz-containing dust in The Netherlands is estimated at 150 000, according to an extensive literature survey in 1993 (26), identifying construction worker subgroups at risk for exposure to quartz. The relative intensity of exposure, presented as an exposure index (27), was later assessed by three experts and combined with the number of workers per occupational subgroup (table 1). Workers with an exposure index of ≥0.2 were considered exposed to levels near and above the Dutch maximal allowable concentration for quartz. The list is not complete, and some occupations at high risk of quartz exposure, such as pile top crushers, are included in some other groups. Carpenters working in maintenance and renovation constituted the largest group (about 80 000). The carpenters were assigned an exposure index of 0.2 on a scale of 0 to 1, but they are likely to experience intermittent exposure to quartz-containing dust.

Study population and study design

In 1998, a cross-sectional study on radiographic abnormalities indicative of pneumoconiosis was conducted among 1335 construction and natural stone workers (28). Only workers with expected high exposure to quartz were selected for the study (N=4173). The participants were selected based on their job title [workers involved in grinding, (jack) hammering, drilling, cutting, sawing, and polishing]. Chest X-rays were made in a mobile X-ray unit. Radiological abnormalities consistent with pneumoconiosis were determined according to median results of three "B" readers (certified by the National Institute for Occupational Safety and Health in the United States) according to the 1980 ILO Classification of Radiographs of the Pneumoconioses (29). Questionnaires were used for the assessment of occupational history, presence of respiratory diseases and symptoms, and smoking habits. Selection bias played a role. It was also expected that the poor agreement between the X-ray readers resulted in misclassification.

In 2002 a case–control study was performed to confirm respiratory disease in association with exposure to dust from construction sites and to describe radiographic abnormalities in more detail. The case–control study was carried out among 96 construction workers from the initial study population with different stages of pneumoconiosis at baseline (24 in profusion category 0/0, 8 in profusion category 0/1, 28 in profusion category 1/0, 17 in profusion category 1/1, 3 in profusion category >1/1, and 8 unknown). This study included high-resolution computed tomography (HRCT) for a total of 79 of the 96 workers and chest X-rays of 93 of the 96 workers. Examinations took place between October and December of 2002 in either the University Medical Center in Utrecht (UMCU) or the Academic Medical Center in Amsterdam (AMC). Three readers classified HRCT scans in Germany. Two NIOSH "B" readers in the US classified the chest X-rays, while a third "B" reader was consulted in cases of disagreement on the outcome. Rounded opacities in the HRCT scans (N=13), rounded opacities in the chest X-rays (N=11), and pleural abnormalities (N=29) were observed in association with elevated cumulative quartz dust exposure. The presence of irregular opacities, indicative of mixed dust pneumoconiosis, could not be reconfirmed in the follow-up study.

Outcomes of the health surveys were associated with a proxy for the cumulative quartz exposure for the assessment of exposure–response relations. Because of a lack of sufficient exposure data, the expert judgment of three industrial hygienists was used in addition to available measurements to rank the exposure of different past and present occupations of the construction workers under study. A semi-quantitative measure of cumulative exposure was calculated by multiplying the duration of exposure by the expert's exposure index (28). This index correlated fairly well with the logarithmically transformed exposure measurements; however, the exposure measurements should not be considered representative of the whole construction worker population, as only a limited number of measurements were performed. Repeated full-shift (6–8 hours) respirable quartz exposure measurements (N=67) were performed for 34 construction workers whose jobs mainly involved concrete drilling, removal of mortar between bricks, pointing, cleaning of construction sites, demolition, and clearing of rubble (9). α-Quartz was determined by infrared spectroscopy. In 55% of the samples, the exposure levels were above the Dutch maximum allowable concentration for quartz (0.075 mg/m^3) (9).

Risk assessment

An accurate risk assessment for the health effects related to exposure to quartz dust specifically for construction workers is complicated. Our studies (27, 28, unpublished data: Tjoe Nij E, Meijer E, van der Drift M, de Meer G, van der Zee JS, Kraus T, et al. HRCT, chest radiography and lung function tests in the evaluation of silicosis and emphysema in construction workers: a case control study), performed to gain insight into the nature and magnitude of silica-induced lung diseases among construction workers exposed to α-quartz, allowed for a first crude estimate on the magnitude of the risk.

Large-scale full-shift exposure measurement programs are lacking for an industry-wide assessment of exposure. Characterizing exposure for construction workers is hampered by the frequent change of worksites and materials worked on. There is also evidence that not only is cumulative exposure associated with the risk of silicosis, but that the risk rises dramatically when exposures are elevated for a relatively short period, as long as a few months (30). Accurate assessment of the prevalence of health effects is hampered by selection bias and misclassification.

We also aimed at determining risks of silicosis and lung cancer for construction workers with expected exposure above the Dutch maximum allowable concentration, based on risk estimates among other occupational groups, such as miners.

Results and discussion

Risk of mixed-dust pneumoconiosis and silicosis among Dutch construction workers

In the cross-sectional study, including 1335 construction workers (average age of 42 years, average duration of exposure of 19 years), a prevalence of 2.9% mixed-dust pneumoconiosis (either predominantly rounded or predominantly irregular opacities of profusion category ≥1/1) was found. Silicosis, as determined by rounded opacities in the chest X-rays, was found for 0.8% of the population. A positive association between cumulative quartz dust exposure and radiographic abnormalities (profusion category ≥1/1) was observed (28). However, the agreement between readers was poor. In this study, chest X-rays were made in a mobile unit, which might have influenced the quality of the films.

Based on the results of the exposure measurements and the duration of exposure of the 1335 construction workers, the average cumulative quartz exposure for this population was roughly estimated at 5.7 mg/m^3-years (31). The prevalence of 0.8% of persons with early signs of silicosis was lower than in other studies (32–35) with comparative exposures. The nested case–control study (average age of 49 years, average duration of exposure of 25.5 years), performed 4.5 years later among 96 persons, showed that rounded opacities in both the HRCT scans and the chest X-rays were present in lungs of a larger number of workers (13 out of 79 HRCT scans and 11 out of 93 X-rays) (unpublished data: Tjoe Nij E, Meijer E, van der Drift M, de Meer G, van der Zee JS, Kraus T, et al. HRCT, chest radiography and lung function tests in the evaluation of silicosis and emphysema in construction workers: a case control study) than expected from the results of the baseline study. In the followed group of 96 workers, only 5 had rounded opacities in their chest X-rays in the initial study, of which 3 could be confirmed at follow-up. Eight to ten new workers with rounded opacities were seen in the follow-up. This finding could not be explained by progression, because the follow-up period was only 4.5 years. The use of techniques with a higher resolution was likely to result in a better classification of silicosis. This possibility was also confirmed by the good agreement between the readers. Lower grades of silicosis and emphysema can be determined more precisely with HRCT (36). When comparing the results of the chest X-rays with the HRCT outcomes, both from the follow up study, we noted a fair sensitivity (50%) for rounded opacities on chest X-rays relative to the HRCT outcomes and a high specificity (94%). A positive association between the presence of rounded opacities and cumulative exposure was observed. The radiographic abnormalities in the follow-up study were likely to be indicative of early signs of silicosis.

According to the results presented in table 2, the prevalence in the whole initially invited population was estimated as if the whole population would have been studied again with HRCT and radiography in hospitals. It was estimated that 185 of 1291 (14%) workers would be positive for rounded opacities in the HRCT scan if the entire baseline study population would have been studied with HRCT in 2002, on the basis of a positive predictive value of the chest X-rays in 1998 of 60% [95% confidence interval (95% CI) 17–100%] and a negative predictive value of 86% (95% CI 79–94%). It was estimated that 121 of 1291 (9%) workers would be positive for rounded opacities in the chest X-rays if the whole baseline population would have been studied again in 2002 in the university hospitals, based on a positive predictive value of 60% (95% CI 17–100%) and a negative predictive value of 91% (95% CI 84–97%). For the whole initially invited population of about 4200, nearly 600 of these workers would have been expected to be identified with rounded opacities in a HRCT scan, if it is assumed that the prevalence of the cases and controls reflects the prevalence of the whole baseline population. These estimates have to be interpreted with great care because the case–control study was carried out among a small number of workers, the average age was somewhat higher, and we did not weigh for exposure years or exposure intensity. How many of these workers will develop silicosis in association with considerable respiratory impairment is still to be determined.

In addition, selection bias probably affected the results. However, these results indicate that the prevalence of workers with radiographic changes consistent with early signs of silicosis (rounded opacities, often in combination with silicotic pseudo plaques) is calculated to be one order of magnitude higher when silicosis is diagnosed with radiographic techniques in hospital settings, relative to the earlier estimate of 0.8% in the baseline study, where chest X-rays were made in a mobile unit. The prognosis for the groups with rounded opacities was presumed to be in accordance with the progression of disease found in other occupational groups with classical silicosis.

Table 2. Crude prevalence of parenchymal and pleural changes found with HRCT (high-resolution computed tomography) (consensus readings and average scores) and chest radiography by invited subgroup. Workers with HRCT results: 19 in category 0/0, 6 in category 0/1, 26 in category 1/0, 17 in category 1/1, 3 in category >1/1, 13 in catogory "unknown", and a total of 79. Workers with X-ray results: 24 in category 0/0, 8 in category 0/1, 28 in category 1/0, 17 in category 1/1, 3 in category >1/1, 8 in catogory "unknown", and a total of 93.

	Selected subgroup on the basis of profusion category as determined in 1998																		Total		
	0/0			0/1			1/0			1/1			>1/1			Unknown			N	%	Score
	N	%	Score [a]	N	%	Score	N	%	Score	N	%	Score	N	%	Score	N	%	Score			
HRCT results																					
Rounded opacities	2	11	2.7–3	0	·	–	6	23	–	1	5.9	–	3	100	–	1	13	–	13	16.5	2.7–10
Irregular opacities	2	11	1.5–3.5	2	33	3.7–6.7	4	15	3–7.8	6	35	9	1	33	4–10	2	25	5	17	21.5	1.5–6.7
Emphysema	3	16	4–5.3	2	33	3–3.3	12	46	2–4	8	47	2–5.3	0	·	4.3	4	50	1.5	29	36.7	4 –14
Pleural changes	4	21	–	2	33	–	8	31	1–9.7	11	65	1.3–14	2	67	–	2	25	2–3.5	29	36.7	–
X-ray results																					
Rounded opacities	0	·	–	1	12.5	0/1	3	11	0/1–1/0	4	24	0/1–2/2	2	67	1/1–2/2	2	12.5	0/1	11	12.5	0/0–2/2
Irregular opacities	0	·	–	1	12.5	–	5	18	–	2	12	–	0	·	–	0	·	–	8	9.1	–

[a] Score: the range of the individual average sum score by 3 readers of the profusion of rounded opacities (minimum=0; maximum=18) or the range of the individual average sum grade by 3 readers of the irregular opacities (minimum=0; maximum=18) or the range of the individual average sum grade by 3 readers of emphysema (minimum=0; maximum=18) for the chest X-ray score represents the profusion category for either rounded or irregular opacities.

An estimate of the prevalence of the construction workers not regularly exposed to high levels of respirable quartz is likely to be lower. The lack of data does not permit a risk assessment for the rest of the construction worker population.

Risk of silicosis and lung cancer based on exposure data

It has to be noted that the risk estimates for silicosis, as assessed from other cohorts, may not entirely represent the risk among the construction worker population. We cannot account for the modification of the toxic effects of quartz exposure by factors present in the dust. The risk for developing silicosis is expected to be lower among construction workers at similar exposure levels, because it is assumed that impurities present in respirable dust from construction sites, such as iron and aluminum salts, can reduce quartz toxicity (37, 38). The percentage of respirable quartz in the air and the associated quartz exposure levels largely depend on the material worked on (table 3), and a wide variety of impurities have been determined as well (9).

An additional lifetime risk for silicosis and lung cancer was calculated as if workers were exposed at 0.1 mg/m^3 of silica during their worklives (45 years), equivalent to 4.5 mg/m^3-years, which is rather conservative. In our study, the cumulative exposure was estimated at 5.7 mg/m^3-years (31), but, as use of respiratory protection was not accounted for, the actual average exposure may have been somewhat lower.

Steenland & Brown (39) have estimated a lifetime risk for silicosis of around 35% up to the age of 75 years for exposure of a worker throughout his or her worklife (from 20 to 65 years of age) to crystalline silica exposure levels of 0.09 mg/m^3 (cumulative exposure of 4.05 mg/m^3-years) (39). A cumulative exposure of <0.5 mg/m^3-years was associated with an excess risk of <1%. Cases were defined as decedents with silicosis on their death certificates or men with radiographically diagnosed silicosis during two cross-sectional surveys. This estimate has to be interpreted with care because it has been extrapolated from a study on younger workers and involved only one cohort. Other studies among miners show higher estimates (32, 40, 41). The association was not considered to be linear, and Finkelstein (42) calculated that the lifetime risk of silicosis drops below 5% when quartz exposure is reduced to below 0.05 mg/m^3 (cumulative exposure of 2.0 mg/m^3-years). According to these risk estimates and the exposure levels found for Dutch construction workers, the lifetime risk for silicosis is likely to be >5% for construction workers with expected high quartz exposure.

The risk of death from silicosis up to the age of 65 years was estimated to be 13 per 1000 deaths for lifetime exposure (45 years) to 0.1 mg/m^3 and 6 per 1000 deaths for lifetime exposure to 0.05 mg/m^3 on the basis of data from six occupational cohorts (43). It has been recognized that, due to the underreporting of silicosis on death certificates, the risks are likely to be underestimated. Mostly older workers (>65 years of age) die of silicosis, but death due to silicosis also occurred between 1985 and 1994 in the United States among young adults (<44 years of age) working in the construction trade, while in that same period not one young adult miner died of silicosis (44).

Another adverse respiratory health effect of α-quartz exposure is lung cancer. After the IARC classification of silica as a class 1 human carcinogen in 1997, there has been considerable debate on the validity of this IARC conclusion (37, 45–47). However, since then, more well-designed studies have been published demonstrating that silica exposure is indeed associated with lung cancer (48–50). The risk of developing lung cancer is suspected to be elevated among silicotics (51–53).

Steenland et al (49) have estimated an additional lifetime risk for lung cancer up to 75 years of age to lie between 1.1% and 1.7% (95% CI 0.1–3.6%) for people exposed for their entire worklives (from 20 to 65 years of age) to crystalline silica exposure levels near the occupational exposure limits (0.01 mg/m^3). Silica is a weaker carcinogen than other lung carcinogens present in workplaces, such as arsenic, cadmium and soluble nickel, when measured by mass in air. According to the exposure levels observed in our study, the additional lifetime risk for lung cancer would be of the same order of magnitude. Again it has to be noted that exposure data are only available for the relatively small

Table 3. Percentage of quartz and material-specific quartz exposure levels (mg/m^3) in respirable dust samples of dust from different materials. [a]

Material	N [b]	Quartz content (%)		Quartz (mg/m^3)	
		Mean	Range	Geometric mean	SD
Lime sandstone	6	30	22–41	1.36	3.0
Concrete	15	22	6–53	0.14	3.4
Mortar (grinding)	4	20	14–24	0.26	3.7
Mortar for pointing	3	0.9	0.2–1.2	0.0015	2.9
Mortar and brick	6	12	8–16	0.42	2.5
Brick	1	6	..	0.53	.
Gypsum brick	1	5	..	0.015	.
Rubble	4	5.1	2.6–9.6	0.099	1.3
Floor dust	12	4.4	0.4–9.6	0.016	4.0
Quartzite and lime building block	4	2.6	1–4	0.036	2.0

[a] Only samples from places where workers had worked on the same material during the whole measurement.
[b] Number of respirable dust samples.

group of construction workers with expected high exposure. No risk can be assessed for the rest of the construction worker population.

In the Dutch construction industry, about 150 000 workers are exposed to quartz. The proportion that is regularly exposed to levels above the maximum allowable concentration is unknown. Not all construction workers are at risk for silicosis or lung cancer because of the strong differentiation in tasks and materials worked on.

The data presented and the comparison with other studies convincingly show that risks for silicosis and lung cancer are elevated for a large occupational group. The risk estimates for death from silicosis at levels near the Dutch maximum allowable concentration is between 0.6% to 1.3% (43) and between 1.1% and 1.7% for lung cancer (49). Our data do not permit an exact calculation of the number of construction workers at risk for silicosis or lung cancer, because of insufficient data on exposure. However, if the prevalence of early signs of silicosis is on the order of 9%, as estimated for the study population, action is urgently needed to prevent workers from experiencing respiratory impairment and cancer.

Recommendations

The estimated risks for silicosis and lung cancer for construction workers seem high, although they need confirmation. Silicosis is an incurable disease, but completely preventable by the elimination of quartz exposure. Harmful quartz exposures are not sufficiently recognized in the construction industry, however, and the same accounts for quartz dust-related diseases. The prevention of respiratory diseases related to exposure to quartz dust should receive much more attention by all parties involved (employers, employees, government bodies, and experts such as industrial hygienists and occupational health physicians).

The International Labour Inspectorate and the World Health Organization (WHO) launched an international program aimed at the global reduction and eventual elimination of silicosis (54). WHO recognizes that there is a widespread lack of awareness of the problem and its magnitude, as well a lack of knowledge about available solutions. Underdiagnosis and underreporting are frequent, especially in small enterprises and the construction industry (55). WHO recommends a preventive strategy, based on the primary prevention approach (ie, control of silica hazard at its source). Secondary prevention is recommended as well and should include surveillance of the work environment. When early signs of silicosis are diagnosed, action should be taken to prevent further exposure and stop progression.

It is a major challenge to protect construction workers from overexposure to quartz. The National Institute for Occupational Safety and Health (NIOSH) in the United States issued an alert on silicosis in the construction industry to increase workers' awareness of the health implications of silica exposure. Surveillance guidelines have also been recommended by NIOSH (56). Even though implementing programs to reduce exposure and increase awareness in small and medium size enterprises is complicated, industrial hygienists should take action to lower exposures. Control measures can reduce exposure substantially, although single measures may not reduce exposure levels to below the occupational exposure limits (8, 14, 17). For the development of effective control strategies, insight into determinants of exposure is necessary. A quantitative and scientifically sound evaluation of the effectiveness of the control measures is urgently needed.

Further research

A retrospective cohort study on lung cancer among construction workers, taking into account exposure to quartz, asbestos, and other carcinogens, has to be considered to verify whether exposure to high levels of quartz-containing dust from construction sites is associated with an increased risk of lung cancer and to estimate its magnitude directly. Extrapolating risk estimates for silicosis among workers in other industries, such as gold mines (39), may not result in correct estimates due to differences in the composition of the dust. For more-accurate risk assessments, expert judgment of exposure has to be validated by more extensive exposure surveys.

It is surprising that, for a population at such high risk as construction workers, data are absent with which to monitor their risk over time. For improved assessment of the number of construction workers at risk, a broad exposure assessment program on all construction worker subgroups should be designed and executed. Determinants of exposure and the effectiveness of control measures should be the focus of studies employing full-shift exposure measurements.

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