The Cost Effectiveness of Occupational Health Interventions: Prevention of Silicosis

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Background The failure to recognize occupational health as an economic phenomenon limits the effectiveness of interventions ostensibly designed to prevent disease and injury. Hence, consideration of economic efficiency is essential in the evaluations of interventions to reduce hazardous working conditions. In this paper, we present an analysis of the cost effectiveness of alternative means of preventing silicosis.

Method To evaluate the cost-effectiveness of specific interventions for the prevention of occupationally induced silicosis, we have used the simulation models based on the generalized cost effectiveness analysis (GCEA) developed by the WHO-CHOICE initiative for two representative subregions – namely AMROA (Canada, United States of America), and WPROB1(China, Korea, Mongolia).

Results In both of the two subregions, engineering controls are the most cost-effective with ratios varying from $105.89 per healthy year or disability adjusted life year saved in AMROA to approximately $109 in WPROB1. In the two subregions, the incremental cost-effectiveness ratio of Engineering Controls (EC) looks most attractive. Although Dust Masks (DM) looks attractive in terms of cost, the total efficacy is extremely limited.

Conclusion To the extent that this analysis can be generalized across other subregions, it suggests that engineering control programs would be cost-effective in both developed and developing countries for reducing silica exposure to save lives. Note that this analysis understates health benefits since only silicosis and not all silica-related diseases are considered.

Key words cost-effectiveness of interventions; silicosis; economic evaluation of occupational interventions.

INTRODUCTION

The defining characteristic of occupational injuries and disease is that they occur as a result of the production of goods and services. That is, they are economic phenomena [Wooding et al., 1999]. The failure to recognize this central aspect of occupational health limits the effectiveness of interventions ostensibly designed to prevent disease and injury. Choices of technology, of materials and of forms of work organization are driven and/or constrained by the fundamental economic motives of enterprises and we ignore such considerations at our peril – or, perhaps more precisely, at the peril of workers whose health and well being are at stake. Even in the public sector, which presumably has non-market goals and functions, market-based evaluation criteria have come to be accepted widely as legitimate. For the purposes of public regulatory policy, consideration of economic efficiency is essential, particularly in developing countries where resources are scarce, development objectives are paramount, and international financial agencies influential. All actors – management, labor, government agencies, health professionals, and advocacy organizations - need to know the costs of hazardous working conditions and of their remedies. Unquestionably, they also need to know many other things – but to ignore the fundamentals of economic enterprise is a serious mistake (Levenstein, 1996).

In this paper, we present an analysis of the cost effectiveness of alternative means of preventing silicosis. When benefits are difficult to evaluate in monetary terms such as health benefits, cost effectiveness analysis can be very useful. Once the policy target in terms of the benefits or outcomes is recognized, cost effectiveness analysis helps to evaluate the cost implications of alternative means of achieving the target. For instance one can compare and rank the efficacies of the different interventions for reducing silicosis in terms of dollars that will be required to obtain the policy target or outcome. In this study the benefits or outcomes are measured in terms of Healthy Year Equivalents. The interventions are ranked by the amount of dollars ($) spent to obtain an additional unit of healthy year.

Silica is a major component of sand, granite, quartz and most stone. Exposure to fine particles of crystalline silica dust in the course of a working life causes silicosis, an occupational respiratory disease much like the better-known affliction of coal miners, black lung. Silicosis is a disabling and often fatal lung disease that is completely preventable [Wagner, 1995]. Inhaling silica dust causes scarring of lung tissue, which impairs breathing, and may eventually result in death. The disease can progress even after the person has been removed from the dusty environment, because scar tissue in the lungs continues to form in response to the presence of particles embedded in

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the lung tissue. There is no cure. In addition to the primary health hazard of silica exposure, silicosis, there are two other serious concerns. Because the lungs are compromised, silicosis also makes its victims more vulnerable to tuberculosis; the association between the two diseases is well known since the last century. With the rise of drug resistant tuberculosis, the need to control silica exposure is urgent. Further, the recent designation of silica as a lung carcinogen by the International Agency for Research on Cancer (IARC) makes the control of silica even more necessary [IARC, 1997]. In the US, the National Institute for Occupational Safety and Health (NIOSH) estimated in 1983 that approximately 3.2 million workers were potentially exposed to crystalline silica, and the US Dept. of Labor estimated that 60,000 people are at risk for developing some degree of silicosis [Harley et al., 1996].[1] Two companion papers in this issue describe the global burden of disease due to silica exposure [Driscoll et al., 2005a; Driscoll et al., 2005b].

Silica exposure occurs in numerous industries. The high-risk sectors of the economy are construction, mining and mineral processing, and in the manufacturing sector, foundries, pottery and glass. In construction, silica dust is produced during sandblasting, rock drilling, masonry work, jack hammering and tunneling. Mining, mineral processing, stone cutting, pottery and glass manufacturing expose workers to silica dust as well. Foundry work and agriculture are dusty industries. Abrasive blasting operations, that either use silica sand as an abrasive, or blast concrete or cement as the substrate, produce the deadly dust. And shipyards, because abrasive blasting is performed to prepare ships for painting, pose a silica hazard. The manufacture of silica abrasives obviously produces silica dust.

In the following sections, we review the literature on silicosis prevention interventions with the objectives of determining the applicability of macro (economy or industry wide) and/or micro (firm) interventions, estimating their effectiveness in reducing disease incidence, and extracting cost estimates for types of interventions. We employ WHO's methodology [Murray et al., 2000, Lauer et al., 2003] to analyze the data and to make estimates of the cost effectiveness of the various interventions for developed and developing countries. We discuss these results and explore their limitations in the subsequent section. Finally, we make recommendations for action concerning the prevention of silicosis and for further research.

DATA

Types of Intervention

The nature of interventions to control silica varies from industry to industry and is dependent on the task or the process being used. For example, in the construction industry there are numerous dust producing activities – demolition, cutting and sawing concrete, making concrete by mixing dry concrete with water, and abrasive blasting operations to scarify or smooth concrete, or remove paint to prepare a structure for painting. A combination of interventions such as a silica substitute in abrasive blasting and wet cutting and sawing of concrete may both be required in the construction sector. The following gives a brief description of the nature of the interventions chosen for our study based on an extensive literature review and numerous conversations with experts in the field.

Substitution for silica sand

The key to preventing silica exposure is to prevent or minimize inhalation of the dust. The ideal way to prevent silicosis is to remove silica from the entire operation. For example, in most abrasive blasting operations in the construction sector and in the transportation sector (ship and bridge maintenance) substituting steel shot for silica sand, or high pressure water for silica, reduces silica exposure to zero [Greskevitch et al., 2000]. Numerous other substitutes for silica are available, including specular hematite, coal, copper and nickel slags, and aluminium oxide [Greskevitch et al., 2000]. Each has its strengths and weaknesses, and all produce significantly less silica exposure than silica sand. In the US, an estimated 700,000 construction workers are exposed to silica dust, although perhaps only 100,000 are exposed at levels above the present OSHA standard [Linch et al., 1994]. Since the construction industry is so fundamental to any economy, the world wide disease burden is much larger. Further, substituting olivine for silica in some casting operations in foundries also dramatically reduces silica exposure in that process [Greskevitch, 2000; Davis, 1979; Gullickson, 1980; James Mosher, personal communication, 2002].

Wet method

In most industries, however, substitution is not an option, and controlling the dust, through wetting a drilled or ground surface may be the control of choice. Wetting down or misting a surface to be cut or drilled is an old, reliable dust control technique. For example, attaching a hose to a drill or jackhammer will keep the rock or concrete moist reduces dust to almost nothing. Numerous case studies of a variety of construction tasks show marked decreases in respirable dust through either spraying a surface or wetting a blade [Linch, 2002, Susi, 2001, Shields, 2000, Thorpe et al., 1999, NIOSH, 1998]. Respirable dust levels in the construction industry were reduced by 90% using wet methods on cut-off saws in the construction industry [Thorpe et al., 1999]. The researchers noted the importance of maintaining water pressure in the reservoirs.

Silica is a major constituent of concrete. Because concrete is such an important component of modern infrastructure, and requires repair and replacement, it is vital that safe ways to deal with concrete be employed [Linch, 2002]. A recent NIOSH study estimates that SIC code 174 (Masonry, Stonework, Tile Setting and Plastering) may have more workers exposed to crystaline

[1] The 1983 statistic is cited to show that NIOSH has been aware of the extent of this problem for over two decades.

silica than any other 3-digit code, excluding mining and agriculture. It estimates that, in the US, 13,800 workers (1.85%) employed in this SIC code in 1993 were exposed to levels in excess of 10 times the NIOSH REL, that is the Recommended Exposure limit, as opposed to the legal, OSHA Permissible Exposure Limit [Linch, 2002]. High pressure water, or hydroblasting, is an extremely effective way to blast a silica-containing substrate and to cut concrete. No dust is produced because the surface is completely soaked; silica exposure is zero, although it is possible, but unlikely, that silica particles could be inhaled in the aerosolized water droplets. The mining industry includes cutting or drilling stone for building material, or cutting through stone to obtain minerals and metal, as well as processing minerals and metal.

Ventilation Systems

Local exhaust ventilation (LEV) is another method to control dust. This is the dust control method used successfully in the Vermont granite industry for the past 60 years [Rosenberg et al., 1999, Urban, 1939]. Unventilated grinders used to remove mortar between bricks produce high exposures, while simply attaching a vacuum reduces emissions considerably. Exposures in this operation were reduced from 20mg of respirable dust per cubic centimeter of mortar removed to less than 0.2mg/cc of mortar removed with the use of a ventilated grinder [Heitbrink et al., 2001]. Respirable dust levels were reduced by at least 90% using Local Exhaust Ventilation (LEV) on cut-off saws in the construction industry [Thorpe et al., 1999]. In the mineral processing industry, the cleaning chamber reduces the amount of dust that escapes from the bags as they move from the loading station to the stacking station. It is a small ventilated chamber with brushes to clean the bags, and ventilation to collect the escaped product. It reduces dust exposure of everyone in the workplace [Cecala et al., 2000].

Total Exhaust Ventilation (TEV) system can reduce exposures to all workers in a mineral processing building. Clean air is brought in to the building through louvers or doors located at the base of the structure while the dust-laden air is exhausted near the top of the building [Cecala et al., 2000].

Worker Training and Personal Protective Equipment (Respirators)

In any kind of control program, the first step is knowledge of the hazard for both the people who design the work process and the workers themselves. Some interventions are quite simple. If one can train people to stand upwind when they pour a bucket of sand, and to pour it close to the ground rather than from waist-high, minimizes dust exposure and costs next to nothing. Emptying a bag of dry concrete calls for the same, simple precautions, but it requires awareness of the hazard. It is difficult to quantify the effects of training. Pam Susi, at the Center to Protect Workers' Rights, points out the main effect of training is to raise workers' awareness of a hazard enough so that they will demand controls. [Susi, personal communication, 2002]

While the use of respirators is common to prevent silica exposure, it is far from ideal. Respirator programs on worksites are notoriously difficult to maintain [Glindemeyer, 1988, MMWR, 1997]. Respirators must fit snugly, and therefore preclude the growing of facial hair. Further, a study of silicosis in abrasive blasters showed that 79% of the blasters who got silicosis wore replaceable cartridge air-purifying respirators [MMWR, 1997]. For silicosis prevention in high exposure jobs, respirators are insufficient. It must be noted that a respirator limits dust exposure for just one person while co-workers and nearby residents continue to be exposed. Other measures control dust for not just one worker, but all around the worker. For instance, total ventilation of the plant reduces exposure for all employees. Attaching a hose to a drill or a saw that will wet down the dust while stone or concrete are worked benefits the whole work site.

Impact of Interventions on the Incidence of Occupational Silicosis

After a systematic literature search, we were able to capture and present information related to interventions and their effectiveness that is available in published and unpublished literature in Table I and Table II. Exposures are measured using the time-weighted average concentrations for an eight-hour period. The National Institute for Occupational Safety and Health (NIOSH) has recommended that the permissible exposure limit (PEL) for silica be lowered to 0.05 mg/m^3 from the current standard of 0.1 mg/m^3 [OSHA Directives, 1978].

Tables I and II report the silica exposures with and without the interventions for a given task in the construction and mineral processing industry respectively. We may note that the normal silica exposure for the sandblasters in the construction industry is much higher than the normal exposures in other operations. [2]

Table I summarizes the evidence of reduction in exposure through the use of selected interventions from the literature mainly in the construction industry while Table II describes interventions in the mineral processing industry.

Information on exposure reduction in Table III is based on the information provided in Tables I and II. Although the problem of silica exposure in certain sectors of the manufacturing sector, such as iron and steel foundries, glass and pottery is severe, there is very little data available on interventions. Therefore, we are assuming that certain interventions --namely, wet method, Local Exhaust Ventilation (LEV) and training and PPE -- that are applied in the construction and mineral processing industries would also be appropriate for the manufacturing sector as well with similar results.

[2] Shaman estimates that more 1,000,000 US workers are at risk of developing silicosis and of these, 100,000 are sandblasters [Shaman, 1983]. For this reason, many countries have banned the use of silica for abrasive blasting and NIOSH has been recommending a ban of silica as an abrasive for over two decades. Therefore, using silica substitutes in abrasive blasting operations is a high priority.

Cost of Interventions

The costs of the different interventions will vary from region to region, depending on the labor rates and raw material costs. We assumed that the costs of equipment will not vary a great deal worldwide. After an extensive literature search, we found that there is limited information available on costs of interventions.

Substitution for Silica Sand

The cost of abrasive blasting depends on several factors: the cost of the abrasive per ton; the productivity of the abrasive (how fast it "cuts"); if the abrasive can be re-used (recycled); cost of the recycling equipment. While the cost of steel grit is much higher per ton ($600/ ton) compared to silica sand ($40/ton), and requires recycling equipment, because steel requires less abrasive per unit of area and is recyclable, the ultimate cost of abrasive blasting using steel grit is considerably lower than that of silica [Greskevitch et al., 1997]. As shown on Table IV, the annualized cost per hour of abrasive blasting using silica is approximately $25.00 compared to that of steel grit, which is approximately $4.00.

Cost estimates available for abrasive blasting projects [Smith et al., 1996] show that there are considerable economies of scale in surface preparation costs. In other words, the cost per square foot is much lower for larger areas (e.g. 3000 sq. ft) compared to smaller areas (e.g. 200 sq. ft). The range varies from $4 per square ft. to $18.00, with an average of $7.50 per square ft. The cost of hydroblasting ranges between $4 and $20, with an average cost of $10 per square foot of surface preparation.

Wet-Methods

An additional cost of $500 - $2000 is incurred in replacing a dry-cut saw by a wet-cut saw and effectiveness of wet-cut saws for concrete masonry units are reported to reduce silica dust exposure level to the NIOSH REL of 0.05 mg/m^3 [Gressel et al. 1999]. The cost varies depending on whether the model is bought as a wet cut saw or is retrofitted by the contractor. The use of water increases the life of the blade, which helps to reduce the annualized cost of these blades.

Ventilation

As used in mineral processing operations, the cost of installing a Total Mill Ventilation System is $6,000 [Cecala et al., 2000]. The cost of a Pallet Loading Dust Control System is in the range of $6,000 - 8,000 while a Bag & Belt Cleaner Device would cost $10,000. Andrew B. Cecala of NIOSH reported to us: "The pallet loading dust control system and bag and belt cleaner device impacts approximately 15 workers, that is, 5 workers a shift for 3 shifts. The Total Mill Ventilation System impacted approximately 15 workers at the installation in the study, but it could impact many more workers because it lowers respirable dust levels throughout an entire structure. As for local exhaust ventilation, a mortar grinding tool equipped with a vacuum and guard used to prevent dust in mortar grinding operations costs $650." This tool is the intervention that is used in the construction industry as mentioned in Table I [Susi, 2001]. This is a relatively new tool in the US. It has been very popular among bricklayers and the cost is expected to drop in the future.

Methods: Application of the WHO Model

In order to evaluate the cost-effectiveness of specific interventions for the prevention of occupationally induced silicosis, we have used the models developed by the WHO-CHOICE initiative [Murray et al., 2000; Lauer et al., 2003; WHO 2002]. The effectiveness of the interventions is analyzed by using the population model entitled POPMOD.[3]

In order to combine morbidity and mortality resulting from silica exposure, we have employed the WHO notion of Healthy Years Equivalent as "an indicator of the time lived with a disability and the time lost due to premature mortality." Premature mortality is calculated using standard expected years of life lost with model life-tables. Loss of physical capacity is measured using disability weights [Homedes, 2000].[4]

Our results are based on the generalized cost effectiveness analysis (GCEA) developed for the reduction of the risk factor of exposure to silica for two subregions – namely AMROA and WPROB1 chosen to represent developed and developing nations respectively.[5] The goal behind this analysis is to determine how health resources could be allocated across interventions and population groups to achieve the highest possible overall level of population health. WHO Guide to Cost-Effectiveness Analysis provides a detailed discussion of the GCEA and its relationship to the other forms of cost effectiveness analysis in the literature (Tan-Torres et al., 2003).

As discussed in the earlier sections, several interventions differ in their effectiveness as well as in the amount of resources they require. The evaluation of the effectiveness of the different interventions for preventing silicosis is based on a comparison of "what if" scenarios. We assume a "null" scenario where we take into account the prevalence and incidence of the disease if a set of interventions were not implemented. Then we compare the solution of the null or base case with the solution of the model where particular interventions are implemented. The GCEA is unique in its approach to evaluate a set of related interventions with respect to the counterfactual of the null set of the related interventions [Tan-Torres et al., 2003].

Through a three-state population model of diseased, susceptible and mortal states, the number of healthy years lived over a period of hundred years by a population for the "null scenario" (in the absence of interventions) is estimated by looking into historical data and estimating input parameters such as: prevalence rate of silicosis, incidence rate of silicosis, case fatality rates and back ground mortality rates and health state valuations reflecting disability weights due to silicosis.[6] Then the

[3] POPMOD Version 1.1.4 Visual C++

[4] Data on life tables for these regions were supplied by WHO.

[6] Historical data refers to past scenarios when there were hardly any regulations.

same population model is solved again by varying the parameters (e.g. reduced incidence rate) after interventions take place. The difference in the healthy life years gained with and without the intervention gives us the effectiveness of the intervention and is used as the denominator of the cost-effectiveness ratio.

Assumptions and Procedures for Generalized Cost Effectiveness Analysis (GCEA)

An important component of the CGEA is the World Health Organization's model, POPMOD, which is an economy wide model and the data employed is macro in nature. However, all of the data on interventions related to the prevention of silicosis are at the job-site micro level. Hence, we required a procedure to move from the micro-level data to macro level data. Given the data on interventions and incidence reduction at the specific job site, we developed a procedure to extrapolate them to an aggregate economy level. Interventions based on specific case studies at the job sites were used as representative interventions for a specific process used in a particular sector. The methodology used for exposure assessment in the two subregions AMROA and WPROB1 is explained below.

Exposure Assessment Methodology

Proportions of the WPROB1 and AMROA populations currently exposed to silica were estimated by combining data on regional distributions of employment by economic sub-sector [ILO, 2000, World Bank, 2001], European and U.S. data on proportion of workers with exposure to silica by economic sub-sector [FIOH, 2001, Kauppinen et al., 2000], and by age-specific labor force participation rates [ILO, 2002], as shown in Equation 1 [Ezzati et al., 2004]. The calculations were completed for both genders and six age groups for AMROA and WPROB1 for the year 2000.

$$PEP(r,g,a) = EAR(r,g,a) * EPF(r) \sum_{i=1}^{9} (PW(es(r,g)i) * PEW(es(r,g)i))$$

Equation I:
Where:

PEP (r, g, a) = proportion of the population with current exposure to silica, by region, gender and age

EAR (r, g, a) = economic activity rate, by region, gender, and age. EAR is calculated by comparing the number of people in the labor force to the total population, by gender and age group. We did not include children under 15 due to inconsistencies in national labor force data.

EPF(r) = exposure partitioning factor, by region, to delineate proportion exposed at low or at high levels. Workers exposed above the U.S. OSHA Permissible Exposure Limit (PEL) for silica were considered to have "high" exposure, while those exposed below the PEL were considered to have "low" exposure.

PW (es(r, g)i) = proportion of the population working in economic sub-sector (i), by region and gender. Economic sub-sectors consist of agriculture, mining, manufacturing, utilities, construction, trade, transportation, finance, and services (UN, 2000).

PEW (es(r, g)i) = proportion of workers in economic sub-sector (i) with exposure to silica, by region and gender.

Chinese and American employment by economic sub-sectors, exposure partitioning factors, and the economic activity rates are further described in [Nelson et al., 2005].

The data on silica exposure within an economic subsector (PEW) were taken from the Carcinogen Exposure (CAREX) database [FIOH, 2001, Kauppinen et al., 2000], which was based on exposures to European and American workers. To check the validity of applying these exposure data to workers in WPROB1, the literature was searched for estimates of the number of workers in Asia exposed to silica, yielding a range of types of studies, from rough estimates to studies in which air concentrations were measured in workplaces [Zou Changqi et al., 1997, Juengprasert, 1997, Phan Hong Son et al., 1999, Nguyen, 2001, NIEHS, 1999]. With few exceptions, the estimated fraction of workers exposed to silica within economic subsectors is equal to or higher in these countries than indicated by the CAREX. Thus, the CAREX database was utilized in this analysis as a conservative underestimate of the fraction of workers exposed to silica in WPROB1, as well as in AMROA. It was also assumed that within a given economic sub-sector, male and female workers have the same probability of exposure, as do younger and older workers. Combining the above information results in Table V which depicts the proportion of the Chinese and American populations with current occupational exposure to silica, by age group and gender.[7]

[7] It may seem counterfactual that in some cases silica exposure is slightly higher in AMRO-A rather than WPRO-B1. A higher rate

The silica exposure assessment was combined with the age-specific incidence rates of silicosis in persons with low and high exposure to crystalline silica developed for the WHO CRA project [Ezzati et al., 2004, Driscoll et al., 2004]. The rates of incidence, prevalence, and case specific mortality were computed and used as input in the WHO simulation model.[8]

Interventions Evaluated and their Estimated Costs

Based on our literature review, we evaluated five different interventions through the WHO Cost-Effectiveness Analysis (CEA) framework. The five different interventions are: (1)Engineering Controls (EC) which includes wet methods; Local Exhaust Ventilation (LEV) or vacuuming; and Total Plant Ventilation (TPV); (Because of the narrow applicability of silica substitutes, we did not include such substitution in our global projections, although in particular industrial circumstances, this is the most desirable alternative.); Worker training and four variants of personal protective equipment (PPE);(2)Comfort Masks (CM); (3)Dust Masks with filters (DM); (4)Full Face respirators (FFR); (5) Half Face Respirators (HFR).

The engineering control interventions are not mutually exclusive. Since these interventions are applied at the economy wide level and the interventions are process-based, we consider certain combinations of these interventions that are applicable to different sectors to evaluate the interventions for the different subregions. The interventions considered under the category of personal protective equipment are essentially in mutually exclusive categories. We found limited information available on costs of interventions. The engineering control interventions involve large amounts of capital expenditure whereas the implementation of personal protective equipment requires large equipment costs (filters and cartridges) as well as labor costs for training the workers. Discounted annualized costs were calculated for all of the above. The costs of the different interventions vary from region to region, depending on the wage rates and raw material costs. The costs of equipment may not vary a great deal worldwide. As discussed in the earlier sections, even after an extensive literature search, we found only limited information on the costs of interventions.

The above engineering control costs in Table VI for the economy as a whole were obtained by taking a weighted average of the different components of engineering control costs, e.g. wet cutting equipment for construction workers, total plant ventilation, dust control equipment etc. for mineral processing workers. Later the per employee costs were converted to aggregate costs by taking the number of workers that are exposed to silica in the high risk sectors.[9] We assumed that costs of training were primarily labor related and 20% of the total costs for the first four interventions were attributed to wage costs and 80% of the costs were attributed to equipment or capital costs. For engineering control interventions, all costs were assumed to be equipment or capital costs.

The data on exposure reduction with protective gear assumes that workers will adhere to the training instructions. However, in reality there may be significant differences in exposure reductions under "ideal" conditions and "field" conditions. The reduction figures were based on expert judgment under ideal conditions.[10]

Table VI represents the costs of the different interventions in the AMROA and WPROB1 subregions respectively and their efficacy in terms of exposure reduction. We find that training associated with the comfort mask is the least expensive alternative but with the relatively low efficacy of 30 % exposure reduction. Although the initial capital expenditures are high for engineering controls, the annualized costs (based on a ten-year time horizon) look encouraging. We assumed a 10% capital recovery factor (which includes depreciation and market rate of interest) to arrive at the annualized cost for all engineering control equipment. The total cost of each intervention for the first ten years was obtained by taking the discounted sum of the product of per employee compliance cost times the number of employees in the total workforce. A discount rate of 3% was used to obtain the present value. Given exposure reductions for each intervention, we derived incidence reduction figures by calculating the relationship between exposures (TWA) and cumulative exposure and thus derived annual risk for different age groups.[11] A uniform disability weight of 0.43 was used for all age groups. [12]

RESULTS

We find from Table VII that the difference in health outcomes resulting from the various interventions is higher in AMROA compared to WPROB1. The largest difference is for FFR (full face respirator) followed by HFR (half face respirators), DM (dust masks with filters), EC (engineering controls), and comfort masks. Health outcomes are higher for AMROA because life expectancy is higher compared to WPROB1. Therefore, lives saved through interventions contribute more toward the healthy years generated by the model.

In both of the two subregions, engineering controls are the most cost-effective with ratios varying from $105.89 per healthy year saved in AMROA to approximately $109 in WPROB1 as depicted in Table VII. This is considered to be very cost-effective because it is the lowest of all the alternatives as evident from Figure 1 and

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of Chinese employment in agriculture, which has a fairly low rate of silica exposure explains this difference.

[8] We are highly grateful to Tim Driscoll for helping us with these estimates.

[9] We are highly grateful to Tom Mochler OSHA, Economics Division for providing us with important cost information for certain components.

[10] Source: Personal Communication, Tom Mochler, OSHA (Economics Division), October 2, 2002.

[11] We are highly indebted to Tim Driscoll for converting the exposure reduction data for each of the interventions to annual risks for each age group.

[12] The data on disability weight was obtained from WHO.

Figure 2 and would be the first choice option where resources are scarce.

Since wage costs differ for training, the total costs of the interventions vary to a certain extent across the subregions. Although Dust Masks (DM) look attractive in terms of cost, the total efficacy is extremely limited. To the extent that this analysis can be generalized across other subregions, it suggests that engineering control programs would be cost-effective in both developed and developing countries for reducing silica exposure to save lives. Note that this analysis understates health benefits since only silicosis and not all silica-related diseases are considered.

DISCUSSION

We see that there is a substantial literature on the effectiveness of interventions for the reduction of silicosis in industrialized countries, while the data for developing countries is scarce and not detailed enough for our purpose. The data that we have demonstrate that while all of the interventions show some level of effectiveness, the most highly preferred is the complete elimination of the use of crystalline silica and substitution with some other less hazardous material. This has already been accomplished with respect to abrasive blasting in many countries. The economic (cost) data are available for the interventions involving substitution of abrasive blasting material. This method, although extremely effective, has a small impact on the economy as a whole. The economic data that we have for interventions that are more influential in the economy are more spotty. Some data are available for developed countries and we have been forced to make several assumptions in order derive global estimates that are useful.

Most of the interventions require engineering equipment and their costs should not vary to a large degree from country to country. Our analyses point out that engineering control programs are cost effective both in the context of developed and developing countries. However, the lack of available data on silicosis prevention interventions in developing countries is a serious limitation of the present study and should be remedied in the future.

The results from models of the type developed here should be interpreted with caution. No model is perfect and the model used here is based on several inherent assumptions with its share of deficiencies. Hence, the model results should be taken as illustrative and interpreted in a relative sense rather than in absolute terms. However, when the solutions of the model are used to understand the overall efficacy of the different interventions it provides useful insights by taking into consideration the fundamentals of economic analysis that are essential in formulating policy guidelines.

Another obvious question might arise: if the interventions are cost-effective, why are all firms not doing them now? We believe that there are several reasons for that: the health of the workers is not always the first priority for the employers and very often they are more concerned about the shareholders profits; managers do not always have the best interest of the company and workers in mind which is known as the Principal Agent's problem in economics. The existence of asymmetric information works toward the advantage of the employers: revealing high risk unsafe work environment might signal higher wages which the employers like to avoid. Employers may be more interested in the short run rather than the long run health of the company and workers.

Sometimes, managers may be resistant to change for non-rational reasons. The area of managerial decision making about health and safety is an important one to explore: organizational factors, conflicting responsibilities, cultural factors, etc. all are worth investigating.

DISCLAIMER

The views expressed in this article are those of the authors and do not necessarily reflect the position of the World Health Organization.

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TABLE I: Engineering Controls for Silica in the Construction Industry

Task	**Intervention**	**Normal Exp. (8hr. TWA)** mg/m^3	**Exp. w/inter (8 hr. TWA)** mg/m^3	**Silica exposure reduction**	**Source**
Jack hammering concrete	Wet cutting	0.17	0.03	82%	Shields, 2000
Chipping concrete	Wet cutting	0.16	0.03	81%	Shields, 2000
Sawing concrete blocks	Wet cutting	0.113	0.02	82%	Shields, 2000
Dry cutting masonry with portable "chop saw"	Wet cutting masonry with stationary wet saw	2.4	0.055	98%	Susi, 2001
Smoothing concrete walls with hand-held angle-grinder	Wet method	0.18	0.02	89%	NIOSH, Concrete Construction, 1998
Mortar grinding	Local Exhaust Ventilation	2.84	0.059	98%	Susi, 2001
Smoothing concrete walls with hand-held angle-grinder	Mini-vac (LOCAL EXHAUST VENTILATION (LEV))	0.18	0.05	72%	NIOSH, Concrete Construction, 1998
Sandblasting concrete or other silica containing substrate	Hydroblasting	14 mg/m^3	zero	100%	Shields, 2000 Rosenberg, in preparation
Task	**Intervention**	**Normal Exp. (8hr. TWA)** mg/m^3	**Exp. w/inter (8 hr. TWA)** mg/m^3	**Silica exposure reduction**	**Source**
Abrasive blasting a silica-free surface	Sand alternative, steel shot	14mg/m^3	zero	100%	Rosenberg, in preparation, Greskevitch et al. 2000

TABLE II: Engineering Controls for silica in the Mineral Processing Industry

Task	Intervention	Normal exposure (dust) (8hr. TWA) mg/m^3	Exposure w/ Intervention (8 hr. TWA) mg/m^3	Silica exposure reduction	Source
Mineral Processing	Total Plant Ventilation (TPV): 4 Fans	3.114	0.968	69%	Cecala 2000
Stacking Bags	Local Exhaust Ventilation (LEV), Pallet Loading ,Dust Control System	0.82	0.20	76%	Cecala 2000
Transporting Bags	Local Exhaust Ventilation (LEV), Belt and Bag Cleaner Device	0.82	0.14	82.9	Cecala 2000
Mineral Processing	Work Practices: Not Blowing Soiled Clothes	0.45	0.19	57.77%	Cecala & Thimons 1986

TABLE III: Estimated reduction in silica exposure through selected interventions from the literature

Industry	Substitution for silica sand	Wet Method	Local Exhaust Ventilation (LEV)	Total Plant Ventilation (TPV)	Training and Personal Protective Equipment (PPE)
Construction	100% (in abrasive blasting only)	86%	85%		20%
Minerals Processing			79%	70%	50%
Manufacturing (Iron and Steel Foundries, Glass, Pottery)		80%	70%		40%

TABLE IV: Cost Comparison: Sand vs. Steel Grit

	Silica Sand	Steel Grit
Blasting time 4hrs/day x 5 days/wk x 52 wks/yr	1,040 hrs/yr	1,040 hrs/yr
Abrasive use (No recovery using 3/8" nozzle)	520 tons/yr (0.5 tons/hr)	1,300 tons/yr (1.25 tons/hr)
Abrasive use (Using Clemco 3x3 hopper recovery system)	520 tons/yr (no recovery)	6.5 tons/yr 200 cycles /on
Labor use Loading and unloading	346 hrs/yr (40 min/ton)	13 hrs/yr (15 min/wk)
Abrasive cost Average price	$20,800 ($40 /ton)	$3,900 ($600/ton)
Labor Cost Average of $15/hr	$5,190	$195
Total annual cost	$25, 990	$4,095
Total annual savings using Clemco 3x3 hopper recovery system: $21,985		

Source: Greskevitch, Mark F., Groce, Dennis W. And Atkins, Staci E. "Assessment of Substitute Materials for Silica Sand in Abrasive Blasting," *NIOSH*, Sept. 1997.

TABLE V: Proportions of Chinese and American populations with current exposure to silica, by age group and gender

Region	Gender	Proportion Exposed	15-29	30-44	45-59	60-69	70-79	80+
AMROA	Male	0.0248	0.0174	0.0231	0.0216	0.0124	0.0032	0.0016
	Female	0.0052	0.0033	0.0042	0.0037	0.0017	0.0004	0.0002
WPROB1	Male	0.0215	0.0174	0.0211	0.0198	0.0131	0.0062	0.0031
	Female	0.0098	0.0076	0.0088	0.0066	0.0029	0.0009	0.0004

TABLE VI: Cost per employee exposed to silica exposure and Effectiveness

	Annualized cost				
	Training Respirator Half Mask	Training Respirator Full Mask	Training Dust Mask cartridge	Training Comfort Mask	Annualized cost Engineering Control
WPROB1	413.6	510.4	264	88	166
AMROA	470	580	300	100	166
Exposure Reduction	90%	95%	80%	30%	70%-86%

TABLE VII: Healthy Life Years Gained and Total Cost and Average CER ($/healthy years gained)

	Healthy Life Years Gained (in years)	Total Cost $	Healthy Life Years Gained (in years	Total Cost $	Average CER	Average CER
	AMROA	AMROA	WPROB1	WPROB1	AMROA	WPROB1
Engineering Controls(EC)	2,880,119	304,988,924	1,184,154	129,483,316	105.89	109.35
Comfort Mask (CM)	1,654,601	183,726,737	585,740	68,641,179	111.04	117.19
Dust Mask (DM)	2,880,119	551,183,877	1,184,154	205,925,160	191.38	173.90
Half Face Respirator (HFR)	2,880,119	863,523,627	1,184,154	32,261,6913	299.82	272.45
Full Face Respirator (FFR)	3,495,298	10,656,25716	1,498,169	398,123,664	304.87	265.74

Figure 1:Average CER for the Different Interventions (AMROA)

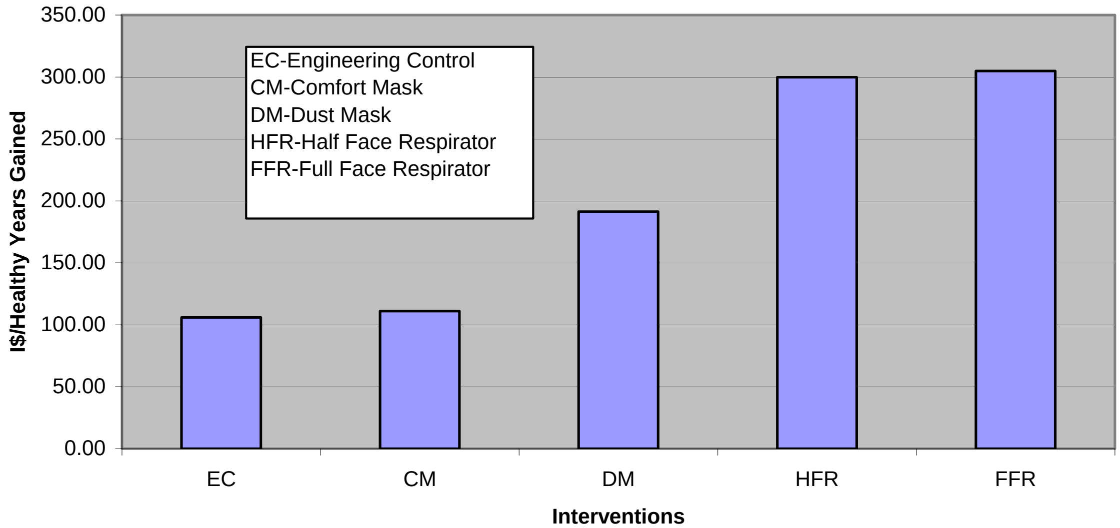

Figure 2: Average CER for the Different Interventions (WPROB1)