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Monte carlo simulation implementation to investigate uncertainty in exposure modeling

Wykorzystanie symulacji Monte Carlo w ocenie niepewności modelu ekspozycji

INTRODUCTION

Exposure levels vary between persons doing the same job and from one day to another or even the work-shift part for the same person. This type of variability results from differences in the way the work is carried out or from changes in the exposure circumstances. Variability in exposure may be the result of simple differences in worker's behavior (eg, "the dirty worker effect") or the difference in environmental parameters. Kromhout at all [13] demonstrated that almost a third of job titles had between-worker variation that spanned an order of magnitude. Although there have been great advances in the technology available to measure the exposure, it is still relatively expensive and time consuming to obtain such data. More complications occur during the open air work (eg. asbestos containing material abatement processes). Therefore, for many current situations, the number of available measurements may be limited, and there may be no reliable data available from the past. This situation has led to the development of several deterministic models that have been used in retrospective epidemiologic studies [8, 11] or in regulatory risk assessments [10]. Cherrie and his co-workers [5] have developed a deterministic exposure model in which the coefficients are assigned by the human assessor on the basis of his or her experience. The model has a simple multiplicative structure that is used to provide a single point estimate of exposure for a given worktask and these estimates can then be combined as a time-weighted average to estimate exposure for work within a specific job title. Guidance is provided for the selection of parameters within the model although there is still a great deal of personal judgment required. The technique has been used in several epidemiologic studies, for example, those by Boffetta et al. [1] and Dick et al. [9], and has been shown to provide reasonably reliable exposure estimates when compared with corresponding measured values [6, 15]. However, it does not take account of the variability in exposure nor the uncertainty in the assessments from the modeling process. The current risk assessment paradigm (e.g., hazard identification, dose-response assessment, exposure assessment, and risk characterization) has been further refined and implemented by several organizations, including the EPA in 1996. These discussions have led to greater understanding of the role of epidemiologic data and deterministic models in risk assessment. Monte Carlo (MC) simulation is a process whereby randomly generated numbers drawn from a given distribution are used to reflect the variability or uncertainty in a deterministic model. The simulation is then repeated many times to produce a distribution of the outcome parameter. With the use of MC simulation it is possible to specify the shape of the distribution for each parameter in the model and to set maximum and minimum values for each variable. Distributions are often specified as one of the following four main types: normal, lognormal, triangular, or uniform. Combining MC simulation with deterministic exposure modeling offers the opportunity to explore the possible variability and uncertainty of exposure estimates. In the present investigation, we chose to use it for the latter purpose. In particular, we investigated whether the reconstructed exposure for two jobs carried out in the same work area are significantly different given the uncertainty in the exposure estimates. We did not consider any uncertainty that might have arisen from the particular model selected or the impact of variation in exposure from between- and within-worker variability. For any given job intra- and inter-worker variability will have a random effect on exposure levels. In epidemiologic studies in which we are concerned with average exposures over a long period of time, this random effect on estimated exposures tends towards zero, some workers having lower exposures one day and higher exposures on others. In this study we were solely concerned with the uncertainty in the value of the parameters selected by the assessor for the model and whether, given this uncertainty, it is sensible to consider exposure estimates for the jobs as distinct.

SUBJECTS AND METHODS

The objective of this study was to examine the uncertainty of generated exposure estimates using previously validated exposure reconstruction methodology. With the use of detailed descriptions of two job titles, it was possible to estimate ranges for model parameters for each job and for each job in different time periods. Using MC iteration techniques, we then calculated the range and distribution of likely exposures within each job. Finally, by contrasting and comparing these exposure distributions, we were able to identify whether or not the jobs were distinct.

This work was carried out as part of a study to investigate the health of workers in the asbestos abatement processes in Eastern Poland. Information about the historical development of the process, and more generally for the whole plant, was obtained using questionnaires and structured interviews with long-service employees as well as epidemiological data. Additional information was provided from company records and disposal plant management. The reconstruction of respirable fiber exposure levels was carried out for two jobs in this area (serviceman and disposal operator). Exposure was estimated for eight distinct time periods, during which process changes, such as the introduction of local exhaust ventilation or changed output of finished products, were identified.

EXPOSURE RECONSTRUCTION METHOD

The strategy for the exposure reconstruction has been described earlier by Cherrie et al. [6] and Cherrie [4]. This exposure model is based on the characterization of emissions from sources in the work environment and the way in which workers interact with the dispersed pollutant. The first part of the model comprises three components: the *intrinsic emission* (e) of the pollutant, the method of *handling* (h) or processing involved at the source, and the effects of any *local controls* (n_{lv}), such as local ventilation. It was assumed that these three factors are all independent and that they act in a multiplicative way, their product being the *active emission* from the source. Exposure can also arise from *passive emission* (e_p) or fugitive sources. *Total emission* from a source is considered to be the sum of passive and active emission.

Two other factors are important in determining the impact of a source: the *time that the source is actively emitting* (t_a) and the use of *personal protective equipment* (n_{ppe}). It was assumed that these two terms also affect exposure level in a multiplicative way; with a reduction in the time the source is active producing a pro-rata reduction in cumulative exposure. Sources can arise in the following two zones: the *near field* or *far field.* The near field is defined as a cube of 2 meters side, centered around the breathing zone of the worker. Sources within the near field act directly to cause exposure. Sources in the far field will have their impact reduced because of dilution or *general ventilation* (d_{gv}).

Exposure sources in the worker's near field (NF) and far field (FF) are then assessed individually according to the following equation:

$$c = [(\varepsilon_i \times h \times (1-\eta_{lv}) \times t_a) + \varepsilon_p](1-\eta_{ppe}) \times d_{gv}$$

The reconstruction of exposure levels for a job title can be carried out by subdividing the work into component tasks or operations and dealing with each separately. It is assumed that individual tasks and the exposure arising from these tasks are independent of each other. By reconstructing exposure levels for both NF and FF sources for each task (*i*) in a job title using the time fraction worked at each task (Δ_i), a time-weighted average exposure level can be estimated (C_T) as shown in the next equation:

$$C_T = \sum_{i=1}^{n} (C_{NFi} + C_{FFi}) \times \Delta_i$$

The descriptive information gathered from questionnaires and employee interviews was summarized, and the time between the start of the vacuum-forming operations and 1995 was divided into a number of time periods for assessment. Two of these periods were chosen to coincide with existing sets of cross-sectional occupational hygiene measurements [3,12].

With the use of MC methods with the Statistica 9.1. software package, model parameters were assigned distributions on the basis of data gained from the questionnaires and interviews. Because the point-estimate reconstructions were made within a spreadsheet, incorporating the MC simulation was convenient. It is also possible to simultaneously model two or more jobs that have linked parameters by pasting these data into dynamically linked spreadsheet pages. Either a triangular or uniform distribution was used for each parameter. For the triangular distributions the model allows the minimum, midpoint, and maximum values to be specified; in the table this specification is shown as 0.2, 0.3, and 0.4. For the uniform distributions, only the minimum and maximum values are specified.

For example, for the emission parameter, a triangular distribution with minimum and maximum values of 0.2 and 0.4, respectively, was employed. This distribution was assigned on the basis of the subjective judgment of the user, and the spread indicated the likely range of values within which the user feels the true value lies. Local ventilation and respiratory protection were not incorporated into the MC simulation because neither was used at the time relevant to this simulation.

Where the same numerical parameter value was used in several tasks in the single point estimate the same random number was pasted into the spreadsheet cells in each case rather than a different random number being chosen. Because both jobs were carried out in the same area the near- field exposure contribution of one job was taken as the basis for the far-field contribution to the other, and vice versa.

Using MC iteration, the model for both the molding operator and serviceman jobs was run using the parameter distributions. Five thousand iterations were run for each job title and the output exposure distributions produced. An analysis of the distributions was carried out to provide values for the mean and 5-95th percentile exposure levels.

RESULTS

The measured respirable fiber concentrations during asbestos abatement process for the period 1997-2002 were known, and the exposure estimates for this period were therefore adjusted to correspond approximately to the measured values. The exposure levels for the remaining time periods were then adjusted by multiplying by the figure for the 2002 measurement divided by the 2002 estimate.

The results from the MC simulation for period 2 (2002-2007) showed that the plant operator and serviceman had considerable overlap in the distribution of the estimated exposures. Figure 1 shows the distribution with the 5th and 95th percentile values for the estimated exposures of both jobs.

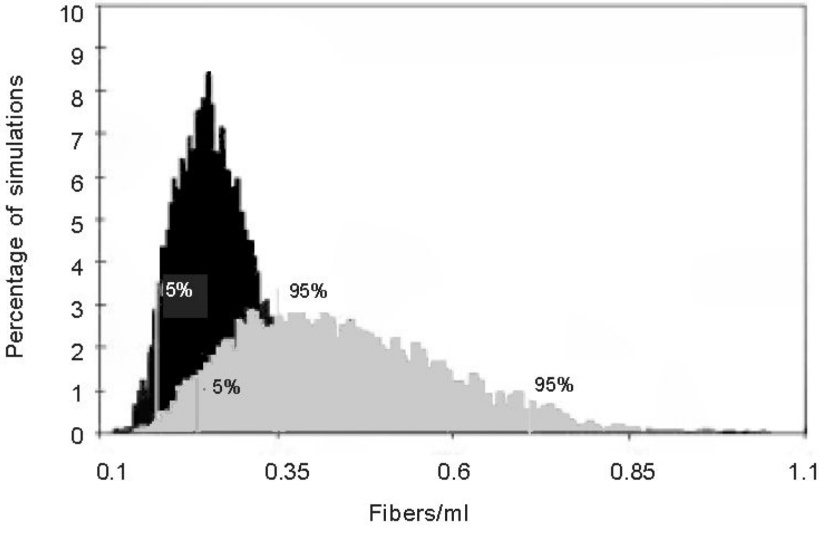

Figure 1. Distribution of modeled exposure levels for the jobs of plant operator and serviceman for asbestos abatement process

The serviceman's mean estimated exposure level (0.44 fibers/ml) was approximately twice that of the molding operators (0.25 fibers/ml). In addition, the molding operators had a much narrower distribution of estimated exposures, 90% of the estimates being between 0.18 and 0.35 fibers/ml. This situation is in contrast to that of the serviceman, who had a much wider distribution of estimated exposures, 90% of the data being between 0.25 to 0.72 fibers/ml. All of the distribution of molding operator exposure was within the serviceman's distribution.

As noted earlier, the models for these jobs were not independent because of common parameters (eg, intrinsic emission) and because they were undertaken in the same building; plus we used the near field from one for the far field of the other. Using the MC simulations across all periods, we found that the correlation between the estimates for the two jobs was 0.7. We further investigated the effect of the correlation on the estimated exposures by taking the ratio of each simulation output for the two job titles for period 2 (Fig. 2). It became apparent that the serviceman had a greater estimated exposure concentration in over 98% of all cases.

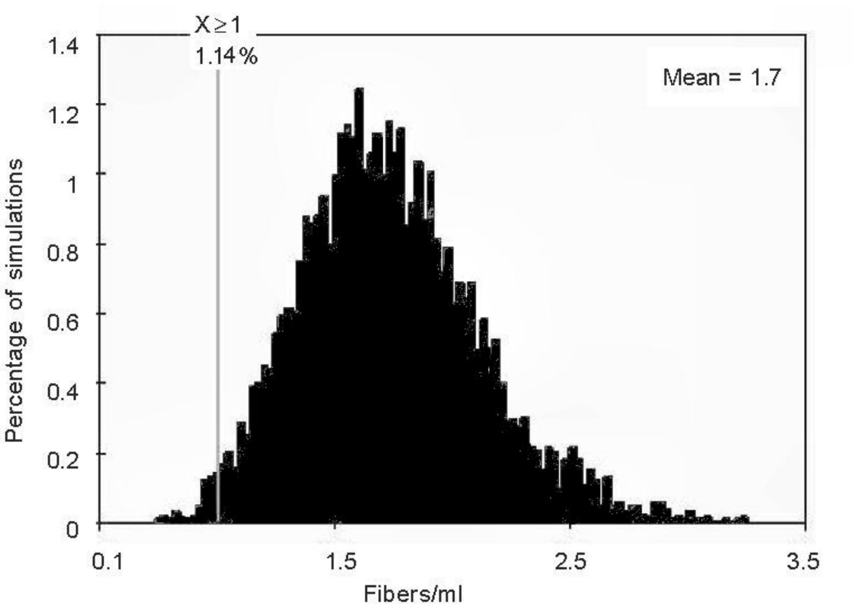

Figure 2. Distribution of ratio for the jobs of plant operator and serviceman for asbestos abatement process

DISCUSSION

The previous work has employed MC simulations for risk assessment purposes [16] or to gauge variability in exposure estimates. However, a recent study by Nicas & Jayjock [14] utilized MC simulations to determine uncertainty in exposure estimates produced by modeling as opposed to monitoring. An analysis of variability in monitoring results led the authors to suggest that in circumstances in which the geometric standard deviation of the exposure distribution is greater than 2.3, mathematical modeling is a more cost-effective and reliable method of estimating the mean exposure level when three or less exposure measurements are available.

The current study also uses MC analysis to examine the uncertainty of exposure estimates. An initial analysis of the available data relating to the molding operator and serviceman indicated that these two jobs were closely related. It was unclear whether there was sufficient difference to warrant their continued separation for the purposes of any epidemiologic study. Using our exposure model to reconstruct exposure levels suggested that the serviceman had exposures that were about double those of the plant operator throughout the period under study. However, there was uncertainty in many of the model parameters, and, therefore, it was difficult to know if the differences in the estimated exposure level were sustainable.

The importance of accurate exposure classification in epidemiologic studies is well understood. Misclassification of exposure generally gives rise to bias so that any relationship between exposure and response may be underestimated, perhaps even obscured entirely [2]. It is therefore important to maintain differences between estimated exposures when justified, and we believe that the method described in this report can be used to identify when real differences exist.

This type of correlation between model parameters is more likely to reflect real-life situations than simplistic assumptions of independent actions. The relationships of model parameters should be fully explored when MC simulations are carried out to examine uncertainty. Many examples of interconnectivity within models exist. These examples may take the form of physical or behavioral influences. For example, physical relationships clearly apply to time periods – a longer time spent on one task will necessarily reduce the time available for another task in a workshift. Behavioral influences can include the increasing likelihood of using control factors when longer tasks are performed or when concentrations reach levels that can be detected by smell or trigger symptoms. In general, these physical and behavioral interrelationships act to reduce the uncertainty of the generated exposure levels, and their identification and incorporation into models can only improve the reliability of the produced estimates.

Models are also used in regulatory risk assessments for occupational exposure. MC simulations have been used to help determine the risks to health from benzene [7] and ethylene glycol ethers [17]. Cox [7] combined MC uncertainty analysis and a physiologically based pharmacokinetic (PBPK) model to demonstrate that benzene exposures of less than 1 ppm do not increase the risk of tumor development.

Our study shows how MC simulation can be successfully used to incorporate uncertainty in model parameters and to identify differences when they exist between occupational groups. There is a need for more work to characterize both the interdependency of used parameters in probabilistic models and the typical variability of these parameters. The parameter values used in the generation of exposure levels were assigned subjectively by an expert using data from worker interviews. More validated information is needed on the parameter values, and detailed guidance or a structured approach for assigning parameter distributions should be developed.

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SUMMARY

This study used Monte Carlo (MC) simulation to examine the influence of uncertainty on an exposure model and to determine whether a difference exists between workers groups in asbestos wastes transportation and decontamination process. Data on work practices and conditions were gathered in interviews with long-serving employees and pilot monitoring process at the asbestos contaminated sites. With the use of previously developed deterministic modeling techniques and likely distributions for model parameters, MC simulations generated exposure profiles for the two monitored job conditions. The exposure profiles overlapped considerably, although the average estimated exposure for one job site was approximately double that of the other. However, when the correlation between the model parameters in the two sites was considered, it was concluded that there was a significant difference in the estimates. Models are increasingly being used to estimate exposure. Different work situations inevitably result in different exposure estimates. However, it is difficult to determine whether such differences in estimated exposure between worker groups are simply the result of uncertainty with respect to the model parameters or whether they reflect real differences between occupational groups. This study demonstrates the value of MC simulation in helping define the uncertainty in deterministic model estimates.

Keywords: exposure assessment, modeling

STRESZCZENIE

W badaniach zastosowano symulację Monte Carlo (MC) w celu uchwycenia wpływu niepewności na przydatność modelu ekspozycji w warunkach zróżnicowanej ekspozycji grup pracowniczych w procesie transportu, demontażu i unieszkodliwiania odpadów zawierających azbest. Dane odnośnie procedur roboczych pozyskiwano zarówno w odniesieniu do pracowników pracujących w warunkach ekspozycji na azbest przez wiele lat, jak również w warunkach nowopowstających stanowisk demontażu i unieszkodliwiania odpadów azbestowych. W odniesieniu do wcześniej opracowanego, przy wykorzystaniu technik deterministycznych modelu i odpowiedniego rozkładu parametrów modelu wykorzystano metodę symulacji MC do opracowania profilów ekspozycji dla dwóch analizowanych stanowisk pracy. Profile ekspozycji okazały się w znacznym stopniu zbieżne, chociaż estymowany średni poziom ekspozycji na jednym z badanych stanowisk okazał się dwukrotnie wyższy niż w drugim. Zatem chociaż wykazano korelację parametrów dwóch analizowanych modelów, wielkości estymowane wykazywały znamienne różnice. Modele znajdują coraz szersze zastosowanie w estymacji ekspozycji. Zróżnicowane warunki pracy rzutują na kształtowanie się estymowanego poziomu ekspozycji. Pozostaje jednak trudność w określeniu na ile występujące zróżnicowanie jest wynikiem nieprecyzyjności modelu a w jakim stopniu uzależnione jest realnie występującymi różnicami pomiędzy grupami zawodowymi. Prezentowana praca ukazuje znaczenie symulacji MC w próbie uchwycenia niedokładności modeli deterministycznych.

Słowa kluczowe: ocena ekspozycji, modelowanie