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ORIGINAL ARTICLE

Developing a job-exposure matrix with exposure uncertainty from expert elicitation and data modeling

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Job exposure matrices (JEMs) are tools used to classify exposures for job titles based on general job tasks in the absence of individual level data. However, exposure uncertainty due to variations in worker practices, job conditions, and the quality of data has never been quantified systematically in a JEM. We describe a methodology for creating a JEM which defines occupational exposures on a continuous scale and utilizes elicitation methods to quantify exposure uncertainty by assigning exposures probability distributions with parameters determined through expert involvement. Experts use their knowledge to develop mathematical models using related exposure surrogate data in the absence of available occupational level data and to adjust model output against other similar occupations. Formal expert elicitation methods provided a consistent, efficient process to incorporate expert judgment into a large, consensus-based JEM. A population-based electric shock JEM was created using these methods, allowing for transparent estimates of exposure.

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INTRODUCTION

Job exposure matrices (JEMs) are used to classify job titles based on what is generally known about exposures with particular tasks. In large population-based or occupational epidemiologic studies, these tools are used as efficient, systematic means of converting coded occupational data, usually job titles, into a matrix of possible exposures. JEMs are especially useful when exposure data at the individual level are difficult, expensive, or impossible obtain.[1] Several JEMs have been developed recently, some of them population-based[2–4] and others industry-based.[5–7] JEMs have improved over time, for example, by increased transparency of decision-making using CART[8] and incorporation of task-based knowledge.[9] However, the exploration of the impacts of exposure assessment uncertainty in occupational epidemiology remains in its infancy.

JEMs can be based on a variety of data sources, however, direct measurements for work-related exposures are rarely obtainable for a wide number of occupations, such as is needed in a population-based JEM. In many cases, the measured exposure is not available and often extrapolation is necessary. Even when current exposures are well-characterized, retrospective assessment might be difficult. In all cases, these exposures may be estimated using mathematical models that use available data as inputs.

Experts with an understanding of specific occupational exposures can formulate these models and adjust data model output when they believe it does not provide the best estimate of exposure. Experts can also provide heuristic estimates of exposure when no reliable data are available. Importantly, experts can provide measures of exposure uncertainty for each assignment within the JEM.

Scientists have used various expert elicitation methods to explicitly frame uncertainty for a range of topics, such as light-water nuclear reactor safety, personal exposure to benzene, and PM2.5 exposure.[10–12] Expert judgment has been used to formulate exposure summaries in JEMS,[13] but this rarely includes uncertainty reflecting differences in job conditions or incomplete exposure information available for each occupation. The Bayesian paradigm allows exposure variation on the individual worker level to be estimated by assigning exposure probability distributions with parameters determined through expert elicitation. Expert judgment within the field of occupational hygiene has begun to incorporate Bayesian methods to aid in explicit prior formulations.[14]

The application of JEMs containing uncertainty information can strengthen epidemiological studies by providing credible limits reflecting exposure misclassification biases. Occupational exposure distributions can be used in epidemiological studies to determine how robust results are to inherent exposure uncertainties; exposures are derived from these distributions for subjects using a Monte Carlo sensitivity analysis (MCSA) or Markov Chain Monte Carlo (MCMC).[15–19]

We describe a methodology for creating a novel JEM by integrating expert mathematical models, which use available data as inputs, and formal expert elicitation to obtain exposure estimates and their uncertainty beyond that captured by the data. With these methods, we developed an electric-shocks JEM (described elsewhere) which defines occupational exposures

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on a continuous scale and provides individual exposure distributions for each of 501 occupations coded using 3-digit 1990 U.S. Bureau of Census classification (BOC). We use this electric-shock JEM, which was developed to assign electric-shock exposures in the absence of direct electric shocks measures, as an example.[20]

METHODS

Selection of Experts

Experts were selected in the specialized area of on-the-job electrical exposure and/or injury across a broad range of occupations. They came from diverse backgrounds to reflect an expansive knowledge base beyond a single expertise. Owing to resource constraints, three experts were included in the formation of the shocks JEM: an industrial hygienist (MY), an electrical engineer (MS), and an epidemiologist with a specialty in workplace electrical injuries (DL).

Defining Exposure

During an initial training call, experts reached consensus on the working definition for the exposure of interest, as the proportion of workers in each occupation exposed to frequent occupational shocks, including those not severe or painful enough to be reported. Such data are not available and cannot be measured with classical industrial hygiene instrumentation.

If experts are involved in creating or improving a JEM, elicitors must inquire about quantities that the experts understand best, to overcome linguistic imprecision, improve confidence in their abilities, and to provide consistent measures of the exposure of interest.[21,22] Experts agreed by consensus that although they would have difficultly providing exposure estimates for the exposure of interest, they could provide shock exposure distributions for each occupation using the following closely related definition:

Working Definition

> "Imagine there is a room full of 100 workers selected at random, all of whom had spent their working career (defined as 30-years) in the assigned job category. They are then asked to raise their hand if they have experienced (at least one) painful occupation related electric shock(s) during their working lifetimes. If this experiment is repeated infinite times, in your expert judgment, what is the median proportion of people who would raise their hands? What is the lower 25th percentile you would expect to raise their hands? Upper 75 percentile?"

The working definition captures occupational exposure to shocks that may be painful, but not necessarily severe enough to cause severe injury or death. Additionally, experts believed that for every painful (but not necessarily reportable) shock workers experience, they are likely experiencing many more less-painful, even possibly imperceptible, shocks. The working definition provided a good proxy for the exposure of interest, while allowing experts to think of the exposure in a way that was straightforward given their expert background.

The primary parameter of interest was the median proportion of workers exposed. Elicitors quantified the cumulative distribution function for each occupation with the median, 25th, and 75th quantiles as inputs.[13] The cumulative distribution function method requires the exposure median and two *a priori* defined quantiles to estimate each expert's subjective probability distribution for the proportion of workers exposed to electric shocks.

The distribution fit can be parametric or non-parametric. When fitting parametric distributions, such as the beta distribution, only two percentiles are technically required. However, requiring three percentiles allows the flexibility of non-parametric modeling and permits fitting mixture distributions that are useful for occupations with very low or very high probable exposure.[19]

Available Electric Shock Injuries and Fatalities

Existing injury data on electric injuries and electrocutions came from: the Bureau of Labor Statistics Survey of Occupational Injuries and Illnesses (BLS SOII) and the Occupational Safety and Health Administration Integrated Management Information System (OSHA IMIS) and are described in Vergara et al.[20] The former provides incident cases of non-fatal shocks, while the latter provides a measure of incident electrocutions. We used the Current Population Survey (CPS), a monthly survey of households conducted by the BOC for the BLS, to construct a proportion denominator for each occupation.[23] Then, we created proportions representing fatal and non-fatal electric shocks separately for each of the 501 3-digit US Bureau of Census 1990 occupational codes (occupations or job titles), which fall into 13 occupational groups. To assure a time frame relevant for application and use in an epidemiologic study, both numerator and denominator data were collected for dates between 1992 and 1999. The data-only proportions are the proportion of workers electrocuted and the proportion of workers seriously injured by electric shock for each occupation per year, p_f and p_{nf}, respectively. These data were used by experts to provide initial estimates of the occupational shock exposure distributions for the working definition.

Batching of Jobs to Streamline Elicitation

To streamline the elicitation process for the current JEM, experts reviewed occupations in batch categories based upon their categorical exposure assignment in a previous ordinal electric shock exposure JEM.[20] Thus, occupations ranked as "High" exposure in the previous JEM were considered first, followed by "Medium" and "Low".

Elicitors further divided job titles within exposure batches into similar occupation groups to make reasonable sizes for experts to assign exposure and to allow for easy comparison of assigned exposures across occupations with similar job responsibilities.

Initial Expert Training

Each expert was sent a training packet providing background, characteristics of the uncertainty, types of elicitation, outline of tasks, contextual causes of biased judgments, a list of experts involved, and academic references relevant to the assessment of occupational exposure to electric shocks.[20,24–28] In addition, we sent experts a description of occupation and industry codes. Experts were trained on judgment biases that may occur including anchoring judgments on imperfect available data and overstating certainty of their estimates.[29] Five test occupations were purposively selected from contrasting occupation groups and were discussed in several training calls arranged to familiarize the experts with the elicitation process. Fatal and non-fatal electrical injury data proportions by occupation were provided to experts in advance.

In subsequent training calls, each expert discussed his initial exposure estimates for the five test occupations, relating in detail the rationale behind median, 25th, and 75th percentile estimates for the exposure. The rationale also included how relative weighting of fatal *versus* non-fatal shock data were reflected by mathematical model (see *Independent expert evaluation*) and the discussion of occupational risks experts considered relevant beyond these data, which only capture exposure to severe electric shocks.

Independent Expert Evaluation

Following the training exercises, each expert independently refined his own model using the fatal and non-fatal injury data as inputs to provide exposure estimates and uncertainty. Each occupation was initially evaluated by two experts to provide experts enough time to focus on assigned occupations given the limited time frame. Each expert weighted fatal and non-fatal injury data differently in their models depending on professional knowledge of the various occupations and assumed exposure risk. Experts 1 and 2 used a weighted average of fatal and non-fatal data to determine initial median exposure, though treatment of data used in each models differed. Expert 3 relied primarily on non-fatal data for initial median estimates. Given the exposure was a proportion, all experts initially estimated the 25th and 75th assuming a binomial distribution, although Experts 1 and 3 used the normal approximation to the binomial. Each expert reviewed the medians, 25th, and 75th quantiles calculated by the models to ensure compatibility with professional knowledge of other occupational factors, such as those in Table 1. Estimates were adjusted if necessary. Detailed descriptions of expert models are provided in the Appendix.

Experts also reviewed exposures for occupations without available injury or fatality data. In these cases, experts considered similar occupations with data and used professional knowledge to assign exposure.

Table 1. Expert determined factors contributing to electric shock exposure for select occupations.

BOC code	*Job title*	*Factors contributing to electric shock exposure*
436	Cooks	Wet environment; low electrical training; appliances ready for use (e.g., toasters, etc.); appliance power cords across or in close proximity to wet work areas; lack of ground fault circuit interrupters; damaged receptacles and/or frayed power cords
453	Janitors and cleaners	Wet environment; low electrical training; appliance power cords across or in close proximity to work areas; damaged receptacles and worn power cords
477	Supervisors, farm workers	Improperly grounded electrical equipment; possible contact with electrical wires routed overhead; work on energized equipment.
483	Marine life cultivation workers	Wet and salty environment; low electrical training; elevated sources (e.g., pumps and motors)
484	Nursery workers	Wet environment; use of electrical equipment after watering plants; low electrical training; work with poorly insulated electrical equipment
583	Paperhangers	Wet environment; low electrical training
865	Helpers, mechanics and repairers	Lack of safeguards

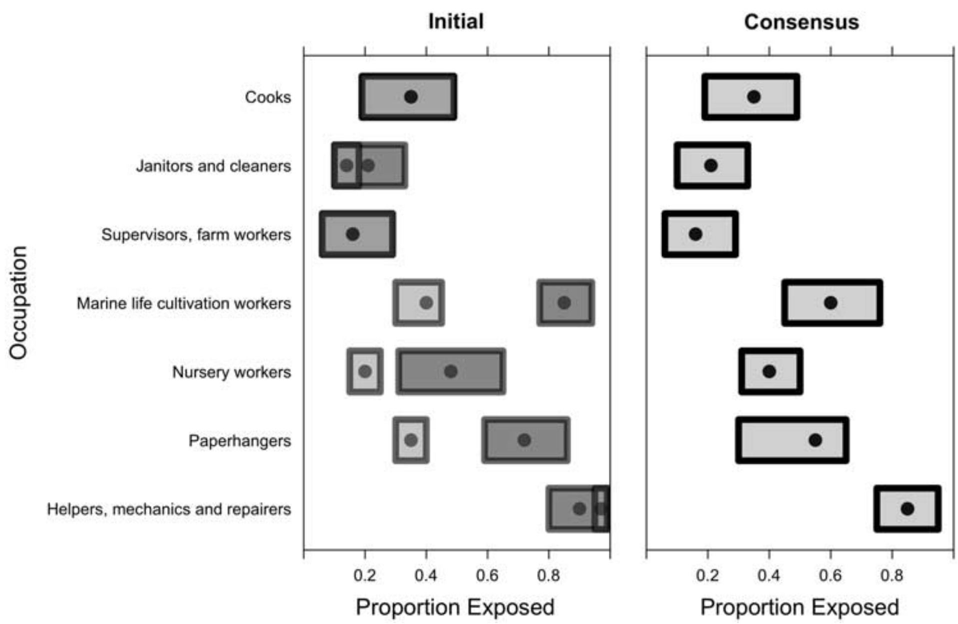

Figure 1. Box plots showing two expert's initial (left) and consensus (right) 25th–75th quantile estimates (medians represented by dark grey dots) for occupations in Table 1.

Elicitation and Working Consensus

Elicitors compiled outputs from models supplemented with expert judgment for the "High" exposure group into handouts given to experts a few days before they met in person to discuss exposure assignments. The handouts organized information supplied by the experts to highlight where and how consensus was not achieved for each occupation and to allow comparison of assigned exposures across similar occupations.

For example, to better diagnose the differences in each expert's estimates across occupations, elicitors classified estimate disagreements for each occupation into disagreement groups for review and discussion: median, uncertainty, and combination. Typically, differences in median estimation by experts meant at least two experts had different estimates by at least 5%. Differences in uncertainty implied a large disagreement on the distance between the 25th and 75th percentiles between experts, typically required to be bigger than 10%. Combination disagreements implied that both medians and uncertainty were very different. Using these classifications, experts could discuss discord in exposure assignment and uncertainty. Each expert was supplied a set of tables which gave all experts' initial estimates and the disagreement type for each occupation, and sorted this information by groups of similar occupations to allow for easy comparison both across and within occupations. The third expert who had not previously examined the occupation during pre-work was to act as a tie-breaker in the event that agreement could not be reached. The third expert also reviewed estimates for which the other two experts had reached agreement to verify these were also in line with his professional expertise.

Elicitors also provided each expert's initial estimates depicted graphically on the same plot *via* boxplots, sorted by similar occupations. The left panel of Figure 1 shows box plots for two experts' initial 25th–75th quantile estimates (medians represented by dark grey dots) for occupations highlighted in Table 1. Box plots show that expert estimates for farm worker supervisors and cooks were consistent, however, other occupations showed disagreement. For example, paperhangers and marine life cultivation workers demonstrated significant disagreement (the former owing to combination disagreement, the latter owing to median disagreement). Experts could also use these plots to verify whether they believed the exposure percentiles compared accurately across occupations in the same plot, given their respective job responsibilities and risks.

Finally, elicitors generated beta distribution plots (pdfs) fit to the 25th, 50th, and 75th quantiles (elicited estimates) for each occupation using the R package risk Distributions.[30] Elicitors used plots to ease understanding of the implied exposure distributions derived from elicited percentile estimates.

Together experts and elicitors used the tables and figures in the handouts to compare estimates during an in-person meeting lasting 2 days. The goal was to arrive at consensus on elicited estimates and uncertainties for the "High" occupations.

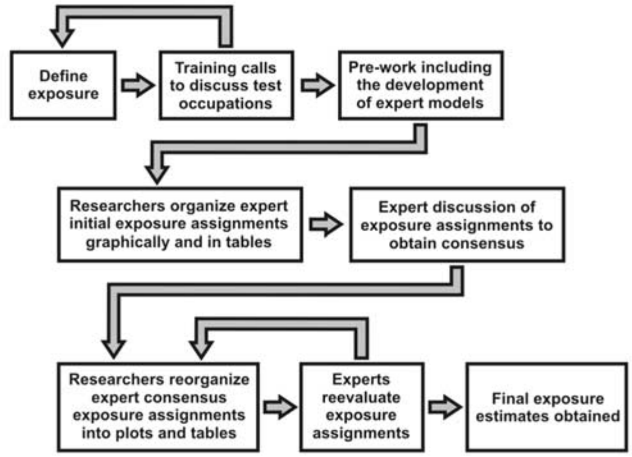

Figure 2. Flowchart illustrating the process of exposure and uncertainty assignments for the electric shocks JEM. The process was iterative at all key steps until final exposure assignment consensus was obtained to allow an accurate ranking of exposures among all occupations. Final estimates obtained by consensus of all experts.

Experts discussed all 103 “High” exposure occupations on the first day, arriving at initial consensus estimates by discussing disagreement types and careful examination of plots comparing like occupations. On the second day, elicitors gave the experts the opportunity to revise previously assigned values or intervals that seemed “too high or low” relative to other occupations by grouping together occupations in a different way: by exposure median categories (greater than 90% of workers exposed to electric shock, between 80% and 90%, between 70% and 80%, etc.). This was done both graphically (using box plots) and in table form.

If experts believed an occupation differed in risk profile for shock exposure from occupations assigned similar exposures, then the occupation was reevaluated, and assigned a new values by expert consensus during the meeting. On the second day, experts also examined revised box plots and tables of occupations grouped by occupation group (for example, for farm worker supervisors, marine life cultivation workers, and nursery workers which are classified as Farming and Forestry occupations) reflecting their consensus estimates from the prior day to verify that new exposure assignments made sense to them within that occupation group. Thus, the process was iterative at all steps until final exposure assignment consensus was obtained between all experts to allow an accurate ranking of exposures among all occupations (Figure 2).

Following the in-person meetings, experts assigned exposures to occupations in the “Medium” and “Low” categories using similar procedures. Elicitors again provided graphical representation of experts’ initial occupational exposures and held a series of conference calls to arrive at consensus-elicited estimates and uncertainty using a same iterative approach.

RESULTS

As a group, the experts assessed 322 occupational titles for the electric shock exposure that had available injury and “electrocution” data. In addition, experts reviewed exposure assignments for 179 occupations not captured by these data. For the first set of 103 “High” occupations, 15 had median disagreement, 13 had uncertainty disagreement, and 29 had combination disagreement.

Additionally, experts revised estimates for 24 occupations assessed during pre-work exercises that were not originally disagreed upon. This was due both to additional input from the third expert who did not provide information on the occupation during pre-work and to revisions occurring on the second day comparing all occupations to occupations with like exposures.

The upper panels in Figure 3 display differences in consensus and initial median exposure assessments (when they occurred) for High occupations by each expert. Expert 3 had the highest number of initial estimates that deviated from the final consensus, which tended to be higher than final median consensus. Experts 1 and 2 tended to have estimates that were neither typically higher or lower than the final consensus estimates, though Expert 1’s estimates tend to be slightly farther from final median choices.

The lower panels in Figure 3 display differences in initial and consensus exposure interquartile ranges, which demonstrate how close an expert’s initial uncertainty estimate was to the final consensus uncertainty estimate. Expert 1 initially specified much larger interquartile ranges for several occupations than the final interquartile ranges reached by consensus, meaning he initially believed uncertainty to be larger than the final consensus uncertainty estimates. The same was true of Expert 2, though to a lesser degree. Expert 3’s initial estimates for interquartile range tended to be slightly narrower, meaning he believed uncertainty to be smaller than consensus estimates.

The batched “Medium” and “Low” occupations had much higher agreement. Experts disagreed on assigned exposures for 26 occupations that were previously in the “Medium” and “Low” occupation groups from the Vergara JEM, 18 of these had combination disagreement, 6 had median disagreement, and none had uncertainty disagreement.

There were no “High” and only two “Medium” occupations without injury or fatality data. Initially, experts disagreed on the two “Medium” occupations, however, the magnitude of disagreement was similar to occupations within this initial exposure category. The majority of occupations without injury or fatality data were office jobs where experts jointly agreed to assign very low exposure.

Figure 4 plots data rates *versus* expert assigned median exposures for each occupation (left) and their respective percentile rankings by occupation (right) for occupations for both non-fatal and fatal injury. Non-fatal injury rates are associated with expert-assigned median assignments (Spearman correlation = 0.89), whereas fatal injury data are associated less (Spearman correlation = 0.39). The percentile rankings for median exposure assignments and non-fatal injury assignments were within 10% of each other for 80% of occupations with data, while only 20% of assigned median rankings were within 10% of the fatal injury data percentiles.

The final electric shock JEM will be presented in another publication,[31] but final median, 25th, and 75th percentile estimates for Table 1 occupations are presented in the right panel of Figure 1, as an illustrative example of the similarities and differences before and after expert assessment.

In this case, original expert-specific estimates were adjusted by consensus for nursery workers and marine life cultivation workers in final expert meetings to form a middle ground between initial expert estimates seen in the left panel of Figure 1. For example, during in-person meetings, the expert with the initial lowest median estimate for marine life cultivation workers did not believe the estimate fully accounted for the wet, salty environment and minimal electrical training. The expert with the highest median estimate believed the estimate over-weighted these risks as this expert‘s initial estimate placed marine life cultivation workers at the same exposure level as electricians and helpers, mechanics, and repairers. All three experts agreed electricians should have much higher exposure risk to electric shock than marine life cultivation workers. The final interquartile range was widened compared with both experts’ initial estimates, reflecting the variation in job conditions and training experts discussed in in-person meetings.

The experts reasoned that janitors and cleaners had similar on-the-job risks as cooks. The experts noted that janitors and cleaners would probably work less frequently in wet environments

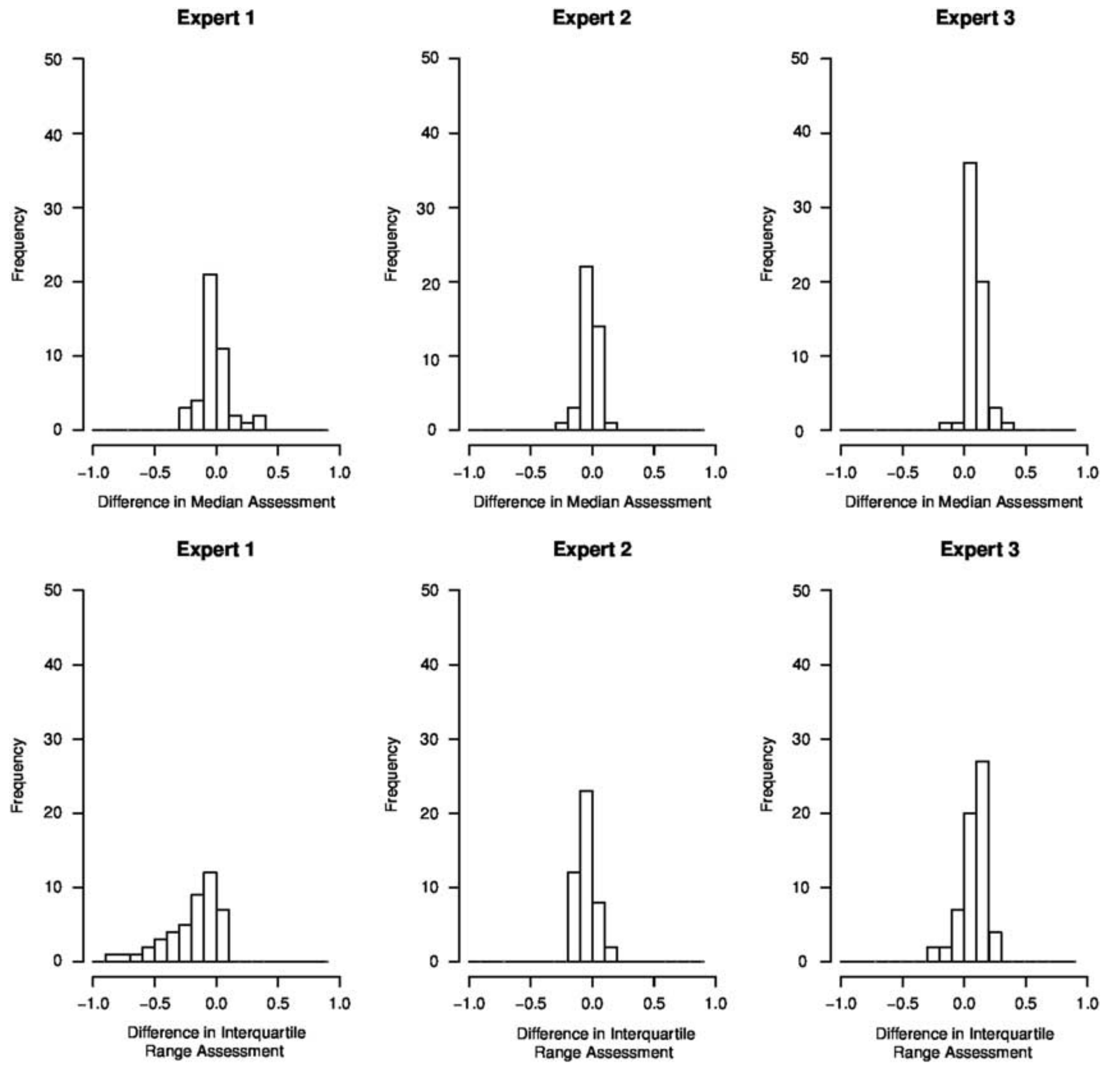

Figure 3. Differences between expert initial and consensus exposure assessments by expert exposure median and exposure interquartile range.

compared with cooks and with portable appliances plugged in only when needed, hence their median estimate is slightly lower. The interquartile range for janitors and cleaners still overlaps with cooks to reflect exposure similarity.

The large disagreement between experts was apparent for paperhangers. One expert with a low median estimate believed it failed to account for the frequent use of electrical equipment in wet environments, for example, paperhangers remove old paper using steam machines. For paperhangers, experts widened the interquartile range and skewed it to the left to allow the possibility of lower exposure because all three experts agreed that common practices using these machines and working with water on the job varied widely, with a subset of workers using them minimally. For all occupations with disagreement in Table 1, wider interquartile ranges were favored to support the larger variations in job practices discussed during expert meetings and not accounted for in expert models.

Rather than acting as a "tie-breaker", the third expert who did not review a particular occupation in prework provided additional perspective and facilitated dialogue about occupations between all experts, allowing consensus on exposure percentiles to occur organically. All experts felt final exposure assignments were accurate and in line with their expertise.

DISCUSSION

Median proportions can be used in future analyses in their continuous form or categorized into a new categorical JEM using different cutpoints. A JEM based on continuous exposure is advantageous, allowing for exploration of cutpoints when there is no biological basis upon which to categorize a particular occupation as "High", "Medium", or "Low" such as for electric shocks. It may also be preferable to use the continuous form as it provides much more detailed exposure information.

An electric shock JEM can be used to provide estimates of exposure for evaluating relationships between occupational electric shocks and health outcomes, in particular ALS.[20] Occupational exposure distributions can be used in future epidemiological studies to determine how robust results are to inherent exposure uncertainties.

We chose an odd number of experts, similar to other elicitation processes,[32] and to avoid ties in exposure assessment. It has been shown that reliability and validity measures were higher for the average ratings than for the ratings from the individual raters and the group's performance can be maximized with three raters.[3] Our study differs from that of Friesen et al. in that is not an industry-based study, but a population JEM covering a large number of

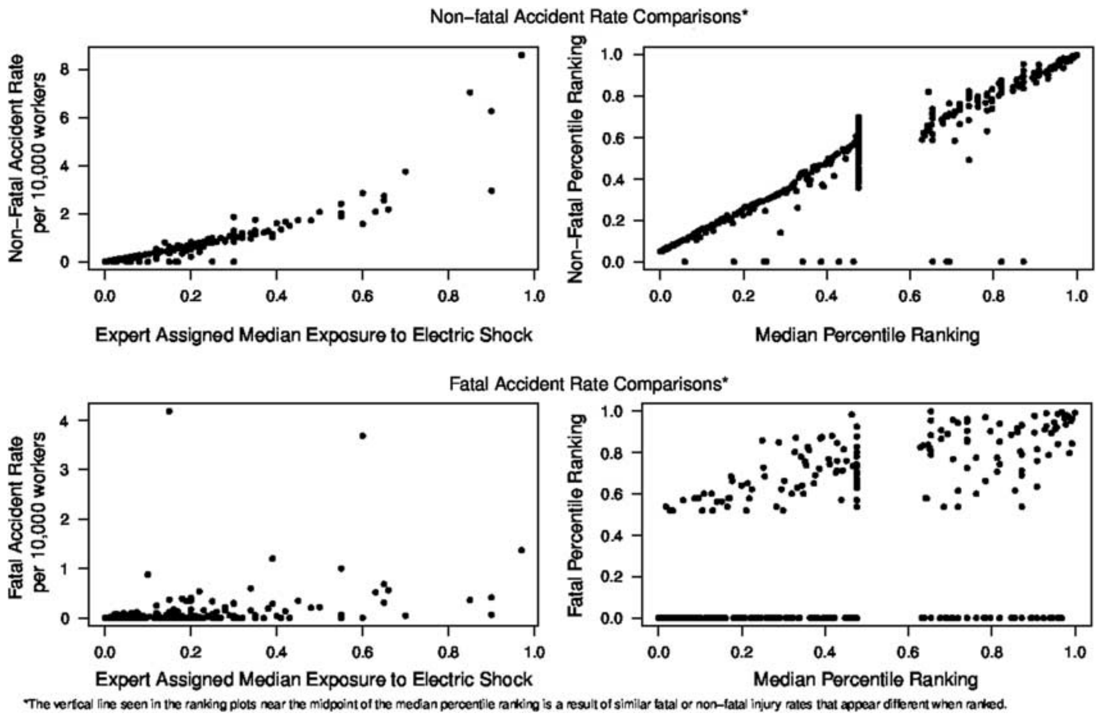

Figure 4. Data rates *versus* expert-assigned median exposures for each occupation (left) and their respective percentile rankings by occupation (right) for occupations for both non-fatal and fatal injury.

industries. Given the wide range of expertise required, we used consensus and cross training rather than the average of independent ratings. Although in principle, this can lead to loss of information, in our case, consensus was easily achieved and our experts felt that final ratings were better than their initial estimates.

Additionally, initial independent expert assessments are available in case they prove useful in future analyses. Though no gold standard is available for JEMs, independent expert assessments may contain some information on the validity of estimates.[33] A categorized version of initial expert assessments can be used in the future to estimate the validity of classification through estimates of sensitivity and specificity from Cohen's kappa alone.[34]

Though expert elicitation significantly strengthens the new JEM, much planning and care must be taken so that the expert knowledge can be elicited correctly and effectively. If experts are involved in creating or improving a JEM, elicitors must inquire about quantities that the experts understand best, to overcome linguistic imprecision, improve confidence in their abilities, and to provide consistent measures of the exposure of interest.[21,22] Communication between experts and researchers is fundamental, and researchers must be flexible in revising definitions of exposure and uncertainty when experts convey that an accurate measure cannot be obtained otherwise. As it was easiest for experts to think of occupational exposure and uncertainty in terms of percentiles using the working definition, we utilized the cumulative distribution function method to elicit expert opinion about the distribution of the proportion exposed to electric shocks. Elicitors initially selected the 5th and 95th intervals; however, experts indicated difficulties in estimating these intervals and definitions were revised accordingly.

Experts in elicitation settings may rely on heuristics. In most elicitation exercises, there is a tendency to "anchor" estimates to or form judgments solely based on available data.[29] In fact, for the electric-shock JEM, experts were hesitant to provide *a priori* exposure estimates without first examining the injury/fatality data. Background data were provided to facilitate elicitation, but it is important to be aware of possible pitfalls in its use. When data are not a direct measure of the exposure of interest, the development of models will only partially alleviate the problem of anchoring.

Additionally, experts may overstate their certainty during elicitation exercises, so specific sources of uncertainty relevant to the exposure of interest must also be emphasized including variation in working practices, job conditions (possibly owing to differing industry), worker characteristics, and each expert's own knowledge of that particular occupation. When believed to be inaccurate, experts de-emphasized data on certain occupations such as chief executives and general administrators who had relatively high fatality rates. Elicitors assured the experts that it was acceptable (and expected) to have fairly large inter-quartile ranges for certain occupations, all of which overlap. Elicitors challenged overconfidence by requiring experts to review occupations with similar job responsibilities and determine whether uncertainty matched the current occupation's assignment.

To further address expert overconfidence and beliefs in data quality, future analyses could use the counterintuitive prior.[35] A counterintuitive prior, a proportion between zero and one, quantifies how certain the experts are about their guess being "right". The prior is given a beta distribution, for example, then used to weight the expert's original exposure percentile estimates with a flat exposure distribution: the more weight placed on the flat distribution, the less confident the expert is with the available data and/or his/her knowledge of exposure information. This application requires asking for double the prior information and may be a logistically difficult feat for population JEM applications with a large number of assigned exposures. However, the method used in combination with the streamlined elicitation processes described in this manuscript may safe guard against expert overconfidence and/or reliance on inaccurate data.

The electric-shock JEM uses BOC 90 coding, which required exposure estimates and uncertainties for 501 occupations. The aspect that distinguishes this expert assessment from other JEMs is the sheer number of required elicited exposure distributions. Other researchers have involved experts to elicit personal exposures;[11] finding great uncertainty surrounding personal estimates as compared with general ambient exposure estimates. However, the number of elicited estimates was smaller in quantity, for example, two concentrations of benzene for two populations.

Industry-based studies typically incorporate expert judgment.[36,37] Although the frequency and intensity of exposure are integrated, rarely do industry JEMs incorporate estimates of uncertainty despite the potential availability of information such as in-house sampling collected to comply with regulation. In a population JEM, industry often cannot be separated from occupation. By providing elicited distributions which accounts for industry to some extent, this population JEM contains a unique feature in that it captures a potentially large source of variation. Further, although numerous examples exist where uncertainty in expert elicitation has been quantified, examples in the epidemiologic literature assessing how this uncertainty impacts risk estimates remain scant. [19]

Developing expert mathematical models, training exercises, additional pre-work, and the iterative structure helped streamline the elicitation process and allowed for transparent exposure estimates. The batching of occupations into similar levels of possible exposures and similar occupations eased the burden on experts. Other information can be used in organizing batch categories for expert elicitation in future JEMs to streamline the elicitation process.

Holding an in-person meeting was important for the first round of discussions concerning “High” exposure occupations as it allowed the experts, some of whom had never met, to communicate more effectively. However, once experts had met in person and went through the elicitation process for the ”High” occupations, we used conference calls as helpful and cost-effective approaches for the subsequent exposure assignments.

Graphical presentation of elicited exposures and uncertainty estimates was not only extremely useful, but necessary to effectively visualize and compare exposure assignments across a large volume of occupations. Experts used this to discern differences between estimates in an occupation group, such as similar manufacturing or construction trades and for occupations with similar median exposure estimates to ensure consistency of exposure assignments. Using the iterative process over time, experts arrived at consensus faster and felt accuracy of provided estimates improved for all occupations.

A weakness inherent to the electric shock exposure is a lack of gold standard or other measurement of accuracy. However, the absence of such a standard is precisely the reason for using these elicitation methods, to create a transparent way to incorporate expert judgment. Comparisons of percentile rankings by occupation between these median exposure assignments and injury/fatality data used in these expert models can be informative. Though expert-supplied exposure medians look very similar to non-fatal injury data for many occupations, experts added valuable information in addition to providing uncertainty information. There were 33 occupations with very low or “zero” non-fatal data percentile rankings, which the experts reclassified to considerably higher exposure percentiles owing to their knowledge of occupational risks. These occupations included roofers, machinist apprentices, farm equipment mechanics, and marine engineers, all of whom are exposed to daily risk of electric shock and highlight the value of expert elicitation in these exercises.

Future work to aid in improving exposure and uncertainty estimates of electric shocks could involve creating independent JEMs, integrating alternate input (injury) datasets and/or involving different experts with mixed expertise for comparison purposes. Multiple JEMs might aid in providing some measure of accuracy in these measures.

CONCLUSION

Moving JEMs from qualitative to quantitative measures and including uncertainty could be very useful in assessment of exposure response relationships. In addition, to providing uncertainty estimates, involving experts in the formation of a JEM has several strengths. Experts can use their knowledge to develop mathematical or statistical models using available data. Additionally, they can supplement exposure values derived directly from data or models to incorporate other aspects of exposure. Using formal expert elicitation is a more transparent way of incorporating expert judgment.

CONFLICT OF INTEREST

Regarding potential conflict of interest, we present the detailed information for each author. Dr. Vergara is currently employed by the Electric Power Research Institute (EPRI), a non-profit research organization geared toward research on generation, transmission and distribution of electricity. Dr. Kheifets has received funding from EPRI for other studies. For this work, Dr. Kheifets was funded, from a Center for Disease Control and Prevention-National Institute for Occupational Safety and Health (NIOSH) grant (5R21OH009901). Dr. Yost is a subcontractor on the NIOSH grant. Mr. Silva has received funding from EPRI and other sources. Mr. Silva, Drs. Lombardi and Yost received NIOSH support for participation on the expert panel. Dr. Fischer also received NIOSH support for work on this project.

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APPENDIX

Appendix Expert Model Descriptions

Expert 1

Expert 1's strategy was to initially estimate the median exposure estimate using a weighted average of the provided proportion estimates for non-fatal and fatal electrical injuries. His model gave greater weight to the non-fatal estimates as the expert considered the injury outcome a broader surrogate for the electrical exposure of interest. The weighted proportions were then projected across a 30-year time period (that is, working lifetime in that occupation). Next, this expert's knowledge of each occupation and the "face validity" of their likely exposure was used to modify the quantitative estimate. Estimates for the 25th and 75th quantiles were initially obtained by assigning a distribution to the final weighted proportion, and setting the 25th and 75th quantiles of that distribution equal to their respective quantiles being estimated. Specifcally, to estimate the 25th and 75th percentiles, he used the normal approximation to binomial distribution and applied a *Z*-score such that $P(z < z0) = 0.25$ and $P(z > z0) = 0.75$.

These estimates were then reviewed to ensure they were consistent with that expert's knowledge of the risks present in each occupation. This expert emphasized the use of occupational knowledge in his methods over models utilizing the data as he felt that provided a more accurate measure of exposure distributions.

Expert 2

To estimate the likelihood of electric shocks in the JEM, Expert 2 adopted a probability model for the risk of electric shocks in each job category. The underlying framework for estimating the risk of shocks was a 2-stage "random box model" which simulates the process of drawing tickets representing a shock or no shock event at random with replacement from a box. The 2-stage model implies there are two boxes. Stage one of the model simulates the probability of shock for the individual worker, who has a fixed probability of getting a shock in each year of his working lifetime (P_{shock}). Stage two of the model simulates the experience of 100 workers who each had this fixed probability of getting shocked during their working lifetime. The box model for stage two is characterized by P_{shock} |30 Yrs, which represents the probability that one of the 100 workers in the room had a painful shock in their working career. This is derived from a binomial model calculating the probability of one worker being shocked at least once in a year given P_{shock} which is itself derived by taking into account both fatal and non-fatal accident rates.

His estimate for P_{shock} was created by assuming it is directly proportional to the probability of non-fatal shocks, $P_{NFshock}$. On the basis of this proportional relationship, then the annual probability of injury, $P_{NF,}$ adjusted to an annual rate from the 8-year proportion QUOTE, is used to estimate the annual risk of a painful shock with a fixed constant: $P_{NFshock} = S_{NF} * P_{NF}$ where S_{NF} is a constant that represents the number of painful shock events per non-fatal injury event. Conceptually, he imagined an event pyramid where there are many shock events occurring, and these events occasionally lead to a non-fatal injury that gets reported.

Next, he generated estimates for P_{Fshock} from the fatal injury data. Accident data from fatal injuries generates a different distribution of risk estimates. To correct this, so that the two distributions were comparable, he applied a power law adjustment to the distribution of P_{Fshock} from the fatal accident data to maximize the overlap in the risk estimates.

The final step was to create an average of the two estimates of P_{shock} from the data in order to find a final estimate for each job category. In cases where there was only one type of injury data (e.g., non-fatal or fatal) available for a particular occupation, he used this estimate directly. In cases where both non-fatal and fatal data were present, upon reviewing the data and based on the expert group discussion, he adopted a weighted average to estimate P_{shock} which would favor the non-fatal data. After the in-person meetings this weight was equal to 0.87.

He obtained P_{shock} |30 Yrs, as the probability of at least one of 30 independent Bernoulli trials, each with a probability of success $P_{shock,}$ resulting in shock. He considered this the median estimate for the working definition. The 25th and 75th percentiles can be evaluated from the inverse cumulative binomial function, which returns the smallest value for which the cumulative binomial distribution is greater than or equal to a specified criterion value, here either the 25th or 75th percentiles, give $P = P_{shock}$ |30 Yrs and $N = 100$, for the 100 people in the room.

This expert placed the most weight on using data models to estimate risk, however, he still adjusted estimates based on his occupational knowledge if the model results seemed unaligned.

Expert 3

The initial assumption is that the non-fatal electrical injury rate is a crude proxy for electric shock potential. Median estimates were initially made for the top five occupations with injury rates that expert experience indicates as clearly having a high median rate (e.g., 95–98%) of exposure to electric shocks. These median accident rates were used to scale in a simple linear manner to other occupations with lower accident rates for an initial estimate for each occupation's median. These median estimates where then carefully reviewed and revised based on expert knowledge of occupations and review of the Classified Index of Industries and Occupations (Bureau of the Census 1990) to understand each job description. In addition, information on electrical injury sources in the workplace (Lombardi 2010) were used to inform the evaluation of the median values. To create rough starting points for 25% and 75% bounds, a normal approximation to the binomial distribution was assumed about the median. These preliminary bounding estimates were then appropriately revised by applying direct knowledge or experience. The 25%/75% estimates were initially thought to be too tight and were expanded to accommodate the 30-year working career criteria used in the process. In addition, the bounds were adjusted to be asymmetric as appropriate using expert judgment for each occupation. To derive the risk estimates for those occupations where expert experience was lacking, a comparison was made with better understood occupations having similar non-fatal injury rates and similar potential exposure sources. Expert judgment was then applied to develop the appropriate estimates.