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Development of an Asthma-Specific Job Exposure Matrix for Use in the United States

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Abstract

Introduction: Existing asthma-specific job-exposure matrices (JEMs) do not necessarily reflect current working conditions in the USA and do not directly function with occupational coding systems commonly used in the USA. We initiated a project to modify an existing JEM to address these limitations, and to apply the new JEM to the entire US employed population to estimate quantitatively the extent of probable work-related asthma exposures nationwide.

Methods: We started with an asthma-specific JEM that was developed for northern Europe (the N-JEM) and modified it to function with the 2010 US Standard Occupational Classification (SOC-2010) codes and to reflect working conditions in the USA during the post-2000 period. This involved cross walking from the 1988 International Standard Classification of Occupations (ISCO-88) codes used in the N-JEM to the SOC-2010 codes, transferring the N-JEM exposure assignments to the SOC-2010 codes, and modifying those assignments to reflect working conditions in the USA. The new US asthma JEM (USA-JEM) assigns exposures to 19 agents organized into five categories. The USA-JEM and N-JEM were applied to the same sample of working adults with asthma to compare how they performed, and the USA-JEM was also applied to the entire 2015 US working population to estimate the extent of occupational asthma exposures nationally.

Results: The USA-JEM assigns at least one asthma-related *probable* exposure to 47.5% and at least one *possible* exposure to 14.9% of the 840 SOC-2010 detailed occupations, and 9.0% of the occupations have both *probable* exposure to at least one agent and *possible* exposure to at least one other agent. The USA-JEM has greater sensitivity for cleaning products, highly reactive disinfectants and sterilants, and irritant peak exposures than the N-JEM. When applied to the entire 2015 US working population, the USA-JEM determined that 42.6% of workers had *probable* exposure to at least one type of occupational asthma agent.

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Declaration
Four of the authors (P.K.H., L.M.K., B.D., and X.L.) are employed by NIOSH. The authors declare no conflict of interest relating to the material presented in this article. The findings and conclusions in this report are those of the authors and do not necessarily represent the views of NIOSH.

Supplementary Material
Supplementary data are available at *Annals of Work Exposures and Health* online.

Discussion: A new asthma-specific JEM for application in the USA was developed. Additional work is needed to compare its performance to similar JEMs and, if possible, to exposure assessments generated on a case-by-case basis.

Keywords

asthma; exposure assessment; job exposure matrix; work-related

Introduction

Work-related asthma (WRA) includes both occupational asthma (OA) that is caused by conditions at work and work-exacerbated asthma (WEA) in which existing asthma is made worse by workplace conditions. WRA is common, with an estimated 16.9% of new-onset cases among adults related to work (Toren and Blanc, 2009), and an average of 21.5% of working adults with asthma having evidence of WEA (Henneberger *et al.*, 2011). Both OA and WEA are associated with considerable lost work time and cost (Vandenplas *et al.*, 2003; Vandenplas and Henneberger, 2007).

Exposure assessment is a critical part of any epidemiologic study because misclassification can adversely impact estimates of exposure–response relationships. Common exposure–assessment methods in epidemiologic studies include self-reports, a job–exposure matrix (JEM), expert judgment, and field measurements. Research indicates that self-reported exposures are prone to misclassification that can result in biased effect estimates (De Vocht *et al.*, 2005). Expert assessment of work histories for individual workers has been used successfully to provide informed estimates of occupational exposure when studying WRA (Milton *et al.*, 1998; Henneberger *et al.*, 2006). However, this approach is resource intensive and impractical in large studies. Field measurements of exposures are objective, but also are often impractical in large studies with participants from multiple worksites and when access to worksites is difficult. A JEM can assign informed estimates of occupational exposures and requires fewer resources than an expert panel. The first asthma-specific JEM was reported in the peer-reviewed literature in 2000, and is frequently referred to as the Susan Kennedy JEM (SK-JEM) after the leading developer (Kennedy *et al.*, 2000). The SK-JEM gave full attention to sensitizers, but did not provide adequate consideration of nonsensitizing irritant exposures. It was recently updated and now includes assessment of both irritant and sensitizer asthma agents (Le Moual *et al.*, 2018).

Researchers at Gothenburg University in Sweden modified the SK-JEM to give full consideration to irritant as well as sensitizing exposures. They developed this JEM for use primarily in northern Europe and called it the N-JEM (Lillienberg *et al.*, 2013, 2014). The N-JEM was developed based on expert judgment and assigns exposure for 18 types of agents. It has been used successfully in a study of severe exacerbation of asthma among employed cases in the USA (Henneberger *et al.*, 2015). However, the N-JEM operates with job codes from the 1988 International Standard Classification of Occupations (ISCO-88), which the International Labor Organization (ILO) developed and maintains (ILO, 1991). While this coding system is commonly used in international studies, it is rarely used in the USA. It would be preferable for investigators working with US populations to have an asthma-specific JEM based on an occupational coding system used widely in the USA, such as the 2010 Standard Occupational Classification (SOC-2010) codes that were developed by the Bureau of Labor Statistics (BLS) (BLS, 2010). Also, while the same jobs in northern Europe and the USA are likely to share similar occupational exposures, it would be preferable to have an asthma-specific JEM that explicitly reflects workplace conditions in the USA.

The first goal of the current project was to develop a JEM that assigns occupational exposures that could contribute to the onset or exacerbation of asthma in the USA during the post-2000 period, and operates with an occupational coding system commonly used in the USA. We achieved this goal by first adapting the N-JEM to function with SOC-2010 occupation codes and reflect workplace conditions in the USA, and then adjusting the initial exposure estimates by evaluating how they compare when the new JEM and N-JEM were both applied to data from a sample of adults with asthma. The second goal was to apply the new JEM to the entire US employed population to estimate quantitatively the extent of probable work-related asthma exposures nationwide.

Methods

Development of the JEM

The development of the JEM during September 2013 through December 2015 is summarized in Table 1.

Cross walk between occupation coding systems and transfer N-JEM exposure assignments to SOC-2010 codes

Jobs can be coded using different occupational coding systems, and a cross walk provides guidance for equating codes from one system to another system. The absence of a single cross walk to transition from ISCO-88 to SOC-2010 necessitated using two cross walks. First, we went from ISCO-88 to ISCO-08 using the cross walk from the ILO (ILO, 2013). To progress from ISCO-08 to SOC-2010, we used the cross walk developed by the BLS and approved by the Standard Occupational Classification Policy Committee (BLS, 2013).

The cross walking yielded 1607 links between the two coding schemes. The 390 ISCO-88 occupation unit groups were each linked to from 1 to 40 of the SOC-2010 detailed occupations. Over half of the 390 ISCO-88 groups were linked to one (n = 64, 16.4%), two (n = 116, 29.7%), or three (n = 56, 14.4%) different SOC-2010 occupations, and the median and mean number of links were 3 and 4.1, respectively. The ISCO-88 group linked to 40 SOC-2010 occupations was code 2310: College, university, and higher education teaching professionals. This was an example where the SOC-2010 system went into greater detail for the one code in ISCO-88.

From the perspective of the 840 SOC-2010 detailed occupations, they were linked to from none (n = 3) to 39 (n = 1) of the 390 ISCO-88 occupation unit groups. The majority of the occupations were linked to one (n = 501, 59.6%) or two (n = 197, 23.5%) ISCO-88 groups, and the median and mean number of links were 1 and 1.92, respectively. The SOC-2010 code with 39 links was 51–1011, first-line supervisors of production and operating workers, and the linked ISCO-88 groups represented a range of specific production settings.

The N-JEM exposure assignments were then transferred to the linked SOC-2010 codes based on the cross walking. This was the first stage of development for the new US Asthma JEM (USA-JEM).

Structural and functional differences between the USA-JEM and N-JEM

Several structural features of the USA-JEM differ from the N-JEM (Table 2). For example, a new exposure category for pest control agents (with the code PEST) was added to the USA-JEM, and the category for Uncertain Exposure in the N-JEM was not retained in the USA-JEM. Descriptions of many categories were changed, sometimes because exposure categories were combined or split. For example, the N-JEM had three separate categories for the low-molecular weight (LMW) agents of acrylates (Category B), epoxies (Category C), and reactive chemicals (Category A). These three N-JEM categories were combined into one highly reactive LMW agents category (with code ABC) in the USA-JEM. Three other N-JEM categories were each split into two. First, Category E in the N-JEM that included organic dusts from both wood and paper became the separate categories of EW and EP, respectively, in the USA-JEM. Second, Category M for cleaning agents in the N-JEM was split into Categories M for cleaning agents and DIS for highly reactive disinfectants and sterilants. Third, the single N-JEM Category O for inorganic dust and fumes became two USA-JEM categories for inorganic dust and fumes: Ometal for metals and Omulti for multiple sources. Another difference with the N-JEM was the designation of *possible* exposure, which meant additional information beyond the occupational code was needed based on specific knowledge of a study participant’s job tasks to yield a final decision of *probable* or *absent* exposure.

Review and modify cross walked exposure assignments

The general lack of concordance between the two occupational coding systems raised questions about the equivalency of codes between the two systems and the accuracy of exposure assignments transferred to SOC-2010 occupations based solely on the cross walking. In addition, it was important to evaluate whether the exposures were truly relevant to workplace conditions in the USA. To minimize errors introduced by the cross walks and ensure that exposures were consistent with working conditions in the USA from 2000 onward, a panel of three subject-matter experts reviewed cross walked exposure assignments and suggested modifications. Two of the experts were industrial hygienists who had many years of experience, one investigating exposure for suspected cases of WRA in a clinical setting and the other following up to confirm reported cases of WRA in a state-based surveillance program. The third expert was an epidemiologist (L.M.K.) with WRA research experience, including studies of workers in manufacturing and healthcare. A physician epidemiologist (E.A.) from Sweden who participated in generating the N-JEM took part in many of the discussions, as did a NIOSH industrial hygienist (B.D.) who was responsible for developing a JEM for chronic obstructive pulmonary disease. An occupational epidemiologist (P.K.H.) with extensive asthma research experience functioned as the project coordinator.

For each exposure–occupation combination, the experts decided whether the exposure was *probable*, *possible*, or *absent*. The guiding principle for *probable* exposure was the same as the N-JEM developers used, with an emphasis on specificity by requiring "a high probability of exposure relevant to work-related asthma for at least half of the subjects with that code" (Lillienberg *et al.*, 2014). The criteria for *possible* exposure was that many workers in an occupation would be exposed, but it did not reach the threshold of at least half of them. *Possible* exposure is intended to become more definite on a case-by-case basis, with the decision made by researchers as they apply the JEM to their own study data. Researchers must decide whether supportive information, primarily in the form of a job description for the individual participant and/or knowledge of exposures where the participant is employed, supports the decision of "a high probability of exposure relevant to WRA" (Lillienberg *et al.*, 2013). In the absence of such convincing participant-specific information, the exposure should be judged as *absent*. In summary, when researchers apply the JEM to their own data sets, the initial assignment of *probable* exposure is made on the basis of occupation alone. In contrast, the label of *possible* exposure requires researchers to use supportive information from their studies to judge whether the individual participant is exposed or not. Every *possible* exposure is eventually changed to either *probable* or *absent*.

The three experts addressed one exposure category at a time, scrutinizing the results of the cross walking for both inappropriate assignment of the exposure to occupations and failure to assign the exposure to other occupations. Initially, each expert worked independently to decide the status of candidate occupations identified as exposed by the cross walking, and which additional occupations (if any) should also be assigned exposure. The decisions from all three were combined and shared with the others, followed by a conference call to review and discuss the experts' decisions. The three experts were then given time (1–3 weeks) to provide their final decisions about which occupations to classify as exposed. The project coordinator retained exposure assignments based on the majority opinion of the three experts. This work involved 20 conference calls during November 2013 through December 2014. The result of this process was an alpha version of the USA-JEM.

Apply alpha version of USA-JEM and the N-JEM to study data

Both the N-JEM and the alpha version of the USA-JEM were applied to the primary current occupations for a cohort of 557 working adults with asthma (Henneberger *et al.*, 2006) and followed by comparing the two exposure assessments for the same occupation. Participants in the cohort study had responded to numerous occupation-related questions about what they did, materials handled, and exposures at work, and this information was available to compare to the exposure assignments. We were especially interested in disagreements between the two JEMs, which we interpreted as opportunities to evaluate whether the new USA-JEM either mistakenly assigned an exposure to an occupation or missed doing so when it should have. Three investigators, one certified industrial hygienist (B.D.) and two epidemiologists (P.K.H., L.M.K.) worked independently to identify such possible errors. Then, they discussed their judgments, made any changes to individual decisions, and used a majority opinion to yield final decisions. The three investigators met 11 times during March through October 2015 to complete this review process. This resulted in relatively few changes to 15 detailed and 2 broad occupations, and yielded a beta version of the USA-JEM.

The 15 detailed occupations with changes included nine with the addition of *possible* exposures (one low molecular weight (LMW), three high molecular weight (HMW), four irritant, and a supervisory occupation in production with all types of exposure), four with the addition of *probable* exposures (all irritant), and two with the deletion of *probable* exposures (one occupation with HMW exposure and another with both a mixed and a peak exposure).

We used the results of applying both the N-JEM and revised USA-JEM to this data set to illustrate similarities and differences between the two. The extent of agreement was measured by calculating the kappa statistic, and interpretation of the kappa score was based on the 1977 publication by Landis and Koch: <0, poor; 0–0.20, slight; 0.21–0.40, fair; 0.41–0.60, moderate; 0.61–0.80, substantial; 0.81–1.00, almost perfect (Landis and Koch, 1977).

Apply the beta version of the USA-JEM to the US workforce

We applied the beta version of the new JEM to the entire currently employed US population, using 2015 Occupational Employment Statistics from the US BLS for the number of workers in the 840 SOC-2010 detailed occupations (BLS, 2016). Only *probable* exposures were assessed, since the absence of job descriptions and exposure information about individual work settings did not allow for decisions about *possible* exposures.

Results

How did exposure assignments change from the alpha version to the beta version of the USA-JEM?

Based only on cross walking from the ISCO-88 to SOC-2010 codes and transferring exposures from the N-JEM, at least one agent was assigned to 448 (53.3%) of the 840 SOC-2010 detailed occupations. During the process of evaluating and revising these assignments, 81 occupations were switched from exposed to unexposed, and another group of 81 occupations was switched from unexposed to exposed, so that the final USA-JEM had 448 detailed occupations with at least one *probable* or *possible* exposure assigned to them. Even though the total number of exposed occupations did not change, the total number of assigned exposure agents increased. Specifically, the alpha version of the USA-JEM had 761 exposures assigned to 448 detailed occupations, for a mean of 1.7 exposures for each exposed occupation. After evaluating the cross walked exposures and revising assignments of agents to yield the beta version of the USA-JEM, the total number of exposures assigned to 448 detailed occupations was 1021, for a mean of 2.3 exposures for each exposed occupation. In other words, the evaluation and revision process resulted in a 34% increase in the number of exposure agents assigned to the same number of detailed occupations.

The number of occupations with different frequencies of agents assigned to them are presented in Supplementary Figure 1 (available at *Annals of Work Exposures and Health* online). Other than for no exposures, the highest frequencies were observed for one agent (n = 278 occupations) and two agents (n = 99 occupations) just after cross walking. After the evaluation and revision process, the number of occupations with one exposure declined to 164, while the number of occupations increased for two, three, four, and five or more exposure agents.

The 840 SOC-2010 detailed occupations are categorized into 23 major occupation groups (MOGs), with 9 to 108 occupations (median = 33, mean = 36.5) per MOG. We compared the assignment of exposures to occupations in the alpha and beta versions of the USA-JEM by SOC-2010 MOGs and by types of exposures. While most MOGs included a similar number of exposed detailed occupations in the alpha and beta versions of the JEM, a few had more substantial changes of 10 or more occupations (Supplementary Table 1, available at *Annals of Work Exposures and Health* online). The SOC-2010 MOG 49-0000 Installation, Maintenance, and Repair had a decrease from 50 to 28 exposed occupations. Many of these newly unexposed occupations had been assigned exposure to acrylates or had uncertain or low exposure based on the N-JEM codes brought over via cross walking (data not shown). Two MOGS had substantial increases in the number of exposed occupations: 25-0000 Education, Training, and Library (from 1 to 14), and 29-0000 Healthcare Practitioners and Technical (from 37 to 54). For the education group, most of the newly exposed occupations had acquired exposure to cleaning agents and/or highly reactive disinfectants and sterilants, while most of the healthcare practitioner occupations had acquired exposure to latex and/or highly reactive disinfectants and sterilants (data not shown).

From the perspective of types of agents, to match assignments from the N-JEM to those from the USA-JEM, it was necessary to combine some categories in one JEM or the other. Also, the comparison of exposed occupations included either *probable* or *possible* exposures as assigned by the final USA-JEM. Only metal working fluids had a decrease of at least 10 exposed occupations (from 32 to 22) (Supplementary Table 2, available at *Annals of Work Exposures and Health* online). However, eight exposures realized an increase of at least 10 exposed occupations: the combination of the USA-JEM categories for cleaning agents and highly reactive disinfectants and sterilants (from 9 to 119); the combination of USA-JEM categories for inorganic dust and fumes from both metals and multiple sources (from 108 to 151); exhaust and smoke from combustion (from 80 to 122); latex (from 42 to 68); risk of peak irritant exposure (from 29 to 51); the combination of organic dust exposure from wood and paper (from 26 to 47); plant antigens (from 17 to 33); and pharmaceutical products (from 9 to 21).

Frequency of probable and possible exposure to WRA agents

The USA-JEM assigns *probable* or *possible* exposure to one or more WRA agents to 53.3% (n = 448) of the 840 SOC-2010 detailed occupations. The occupations with *probable* exposure (399/840 = 47.5%) are over three times more numerous than those with *possible* exposure (125/840 = 14.9%). Seventy-six (9.0%) of the detailed occupations are assigned both *probable* exposure to at least one agent and *possible* exposure to at least one other agent. Of the 399 detailed occupations with *probable* exposure to at least one agent, the majority (227/399 = 56.9%) are assigned several agents: 172 with one agent, 122 with two agents, 63 with three agents, 32 with four agents, and 10 with five agents. The 125 detailed occupations with *possible* exposure follow a different pattern with the majority (73/125 = 58.4%) having one agent and the others having more than one agent: 24 with two agents, 15 with three agents, and 13 with four to 14 agents.

Frequency of exposed detailed occupations by exposure categories and major occupation groups

The most common of the five exposure categories were irritant agents and mixed agents, assigned by the USA-JEM to 39.4% and 20.2% of the detailed occupations, followed by HMW agents (14.9%), LMW agents (13.9%), and peak agents (6.1%) (Table 3, last row). The exposure categories differed by which two MOGs had the highest percentage of exposed detailed occupations (Table 3). Specifically, these two MOGS were 51-0000 Production (49.1%) and 47-0000 Construction and Extraction (40.0%) for LMW agents; 45-0000 Farming, Fishing, and Forestry (100%) and 29-0000 Healthcare Practitioners and Technical (70.5%) for HMW agents; 37-0000 Building and Grounds Cleaning and Maintenance (100.0%) and 31-0000 Healthcare Support (88.2%) for Mixed agents; 35-0000 Food Preparing and Serving Related (94.4%) and 47-0000 Construction and Extraction (93.3%) for Irritant agents; and 33-0000 Protective Service (40.9%) and 37-0000 Building and Grounds Cleaning and Maintenance (40.0%) for Peak agents. The two most common exposure categories also had very high percentages (i.e. ≥80%) of exposed detailed occupations in the following MOGs: 29-0000 Healthcare Practitioners and Technical and 35-0000 Food Preparing and Serving Related for Mixed agents; and 37-0000 Building and Grounds Cleaning and Maintenance and 53-0000 Transportation and Material Moving for Irritant agents (Table 3).

The percentage of detailed occupations in a MOG to which the USA-JEM assigned at least one *probable* or *possible* exposure ranged from 0 to 100% (Table 3, last data column). These percentages are bimodal, with eight MOGs in the range 0–20% and another eight in the highest range of 81–100%, and seven distributed across a broad middle range of 21–80%. Four MOGs have <10% of their detailed occupations assigned to exposure: 13-0000 Business and Financial Operations (0/32 = 0%), 15-0000 Computer and Mathematical (0/19 = 0%), 23-0000 Legal (0/9 = 0%), and 41-0000 Sales and Related (2/22 = 9.1%). At the other extreme, exposure to at least one agent was assigned to 90% or more of the detailed occupations in five MOGs: 35-0000 Food Preparing and Serving Related (18/18 detailed occupations = 100%), 37-0000 Building and Grounds Cleaning and Maintenance (10/10 = 100%), 45-0000 Farming, Fishing, and Forestry (15/15 = 100%), 47-0000 Construction and Extraction (58/60 = 96.7%), and 31-0000 Healthcare Support (16/17 = 94.1%). The most common types of exposures (i.e. assigned to >50% of detailed occupations) varied among these MOGs: HMW, Mixed, and Irritant agents for MOGS 37-0000 and 45-0000; HMW and Mixed agents for 31-0000; Mixed and Irritant agents for 35-0000; and Irritants agents for 47-0000. Supplementary Table 3 (available at *Annals of Work Exposures and Health* online) provides additional detail, with numbers by the 19 agents included in the USA-JEM.

Comparision of USA-JEM and N-JEM applied to the same sample

When we compared the results from applying the beta version of the USA-JEM and the N-JEM to the same sample of working adults with asthma, the kappa for any exposure was 0.54 (Table 4). The kappa scores were in the moderate range of 0.41–0.60 for 8 of the 14 types of exposures we compared. Three exposures had kappa scores less than 0.20, indicating poor or slight agreement. In two of these three instances, the USA-JEM assigned many more workers to exposure than the N-JEM, with 146 versus 12, respectively, for the combined category of cleaning agents and highly reactive disinfectants and sterilants, and 43 versus 6, respectively, for the risk of peak irritant exposure. In the third instance, other HMW biological agents had the weakest agreement (kappa = −0.01) with no overlap between the five exposed participants as judged by the USA-JEM and nine by the N-JEM. Exposures with the best agreement between the two JEMs were plant antigens (kappa = 0.94), latex (kappa = 0.78), and inorganic dust and fumes (kappa = 0.67).

Results from applying the USA-JEM to the 2015 US working population

The USA-JEM assigned at least one asthma-related *probable* exposure to 42.6% of the 2015 US working population. Table 5 includes percentages of the total number of workers that the USA-JEM assigned to each of the 19 WRA exposures. The distribution of these exposure-specific frequencies was skewed to the right, with a range from 0.24 to 20.2%, median of 2.90%, mean of 5.22%, and mode in the range 1.0 to 2.0% with five agents. The two LMW agents and four mixed agents were distributed equally above and below the median, three of the four HMW agents were below the median, and five of the eight irritant agents were at the median or higher. The four most common WRA agents (all >10% of the workers) were: highly reactive disinfectants and sterilants, 20.2%; cleaning agents, 17.9%; exhaust and smoke from combustion, 10.7%; and latex, 10.2%. The three least common agents each accounted for <1% of all workers: organic dust–paper, 0.66%; animal-derived antigens, 0.61%; and organic dust–textile, 0.24%.

Discussion

Summary of major findings

We developed a new asthma-specific JEM that is derived from the N-JEM, reflects working conditions in the USA during the post-2000 period, and functions using an occupational coding system that has widespread acceptance in the USA. The USA-JEM assigns *probable* exposure to at least one asthma-related agent for 47.5% of the 840 SOC-2010 detailed occupations and *possible* exposure for 14.9% of the detailed occupations, and 9.0% of the occupations have both *probable* exposure to at least one agent and *possible* exposure to at least one other agent. The USA-JEM assigns exposure to a high percentage of the SOC-2010 Detailed Occupations in the MOGs of Food Preparing and Serving Related; Building and Grounds Cleaning and Maintenance; Farming, Fishing, and Forestry; Construction and Extraction; and Healthcare Support. When applied to the entire 2015 US working population, the USA-JEM assigned *probable* exposure to at least one work-related asthma agent to 42.6% of workers.

Comparison of USA-JEM to the N-JEM

When comparing the N-JEM to the SK-JEM, researchers reported that the kappa score for any asthma-related exposure was 0.78 (Lillienberg *et al.*, 2014). This score was greater than the kappa of 0.54 when comparing the USA-JEM to the N-JEM for any asthma-related exposure. Several factors may contribute to this lower level of agreement. First, the N-JEM and SK-JEM use the same occupational coding system (i.e. ISCO-88), and were both developed for work organization and conditions in Europe. In contrast, the N-JEM and the USA-JEM use different occupational coding systems and were developed to favor different working populations. Second, the N-JEM and SK-JEM were both developed with an emphasis on OA, while the USA-JEM was developed to be applicable to any WRA, including WEA as well as OA. Third, the N-JEM was developed with the initial goal of assessing exposures for the Respiratory Health in Northern Europe (RHINE) study, with a focus on occupational exposures that occurred during 1980 to 2000. The USA-JEM was developed to reflect exposures post-2000.

The USA-JEM assessed many more worksites as having exposure to cleaning agents, highly reactive disinfectants and sterilants, and peak irritant exposures than the N-JEM. These differences reflect the collective opinion of the experts that these exposures are more common in the USA than was expressed in the N-JEM. It is possible that these categories have become sensitive at the cost of specificity, and represent more inclusive, but also potentially diluted, indicators of exposure. If that has occurred, then they might not be effective surrogate metrics for identifying asthmagens.

Percentage of work force to which the USA-JEM assigns at least one work-related asthma exposure

The observation that the USA-JEM assigned a *probable* work-related asthma exposure to 42.6% of the 2015 US working population suggests that these exposures are very common. The two agents assigned to the most workers were highly reactive disinfectants and sterilants (20.2% of workers) and cleaning agents (17.9% of workers) (Table 5). The products and methods used in disinfecting and cleaning may change over time, and lead to changes in how these activities impact the respiratory health of exposed workers.

The estimate that 42.6% of workers have *probable* exposure to asthma agents at work is similar to findings from two large population-based studies. Investigators in Australia conducted a national survey and inquired about occupational exposure to ~277 asthma agents, and assigned exposure based not only on the job but also the tasks workers conducted in the same job (Fritschi *et al.*, 2016). They estimated that 46.6% of men and 40.4% of women were exposed to at least one asthma agent. When we weight these estimates to the frequency of men and women in the 2015 US working population, the summary estimate was 43.7% exposed, similar to the current estimate of 42.6%. Also, when researchers applied the N-JEM to a population-based sample of ~10 000 working adults in the Telemark region of Norway, an estimated 45.6% were exposed to at least one asthma agent (Abrahamsen *et al.*, 2017). The last example suggests that despite the differences between the USA-JEM and N-JEM in the emphasis on certain agents, the overall frequency of exposure might be very similar.

The percentage assessed as exposed to at least one asthma agent was less in studies that used the SK-JEM. For example, the SK-JEM was used in the Second European Community Respiratory Health Survey (ECRHS-II) (Le Moual *et al.*, 2014). It was applied to the jobs of >7000 participants and yielded a judgment of exposure for 40.6% of the men and 26.8% of the women. When we weighted these estimates to the distribution of the 2015 US working population, the overall estimate was 34.2% exposed. In an older study, the SK-JEM was applied to the ECRHS sample in Spain, with the result that 36.9% of the participants were assessed as likely to be exposed to asthma agents at work (Zock *et al.*, 2004). These lower percentages of exposure could reflect the differences already noted between the USA-JEM and N-JEM, but may also reflect the fact that the SK-JEM is primarily focused on sensitizing causes of asthma while the USA-JEM is intended to consider both irritant and sensitizing causes. It is also possible that the SK-JEM is simply more specific than the USA-JEM.

Strengths and weaknesses

The USA-JEM was developed based on the insights of work-related asthma experts with different types of field and research experience in the USA. It assigns 19 different potential asthmagens grouped in five categories that will allow for analyses that consider the agents both separately and in combination. The fact that it is intended for use in the USA is both a strength and a weakness, depending on the location where researchers intend to evaluate workplace exposure to asthma agents. The decisions about exposure assignments were not based on field measurements, which is considered a superior approach to constructing a JEM (Teschke *et al.*, 2002). Also, the USA-JEM has not been validated relative to exposures assessed for individual study participants.

Next steps

An important next step will be to determine how the USA-JEM performs relative to other assessments of asthma-specific exposures. It might be possible to apply the updated SK-JEM and the USA-JEM in the same sample of working adults and compare the results (Le Moual *et al.*, 2018). Another approach would be to compare the performance of the USA-JEM among cases of WRA in the USA that were confirmed by state-based surveillance programs (White *et al.*, 2014). In these settings, state-based surveillance staff have employed various strategies to assign putative exposures for cases with work-related onset or exacerbation of asthma. Another option might be to initiate a new study of working adults and assess exposure to occupational asthma agents on a case-by-case basis to generate a standard to which the USA-JEM could be compared. While this latter approach is desirable, it would likely be expensive and time-consuming. When we applied the USA-JEM to the 2015 US working population, large numbers of workers were assigned exposure to agents used in disinfecting and cleaning. Because the products and methods used in these activities may change over time, additional research and surveillance are needed to detect these changes and document how they impact the respiratory health of exposed workers.

Conclusions

We developed a new asthma-specific JEM that is intended to represent working conditions in the USA during the post-2000 period, and named it the USA-JEM. It assigns 19 exposures to jobs that have been coded using the SOC-2010 occupation codes. When applied to the entire 2015 US working population, an estimated 42.6% of all workers had at least one *probable* exposure to an asthma agent. Further research is needed to compare how the USA-JEM performs relative to other assessments of asthma-specific exposures, including other JEMs.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Table 1.

Objectives and accomplishments in the development of a new asthma-specific job-exposure matrix (JEM).

Objective	What accomplished
Cross walk from ISCO-88 occupation codes to SOC-2010 occupation codes	Double cross walked from ISCO-88 to ISCO-2008 to SOC-2010. Transitioned from 390 occupation unit groups in ISCO-88 to 840 detailed occupations in SOC-2010
Transfer N-JEM occupational exposure assignments to new JEM	Transferred occupational exposures for ISCO-88 codes as assigned by N-JEM to SOC-2010 codes based on cross walking
Review and modify cross walked exposure assignments	Three work-related asthma experts (two industrial hygienists and one epidemiologist) independently reviewed and modified cross walked exposure assignments, followed by discussions that included input from other experts. Final assignments were made based on a majority opinion of the original three experts.
Apply new JEM and N-JEM to a sample of working adults, compare results, and modify new JEM as appropriate	Applied both JEMs to current occupations of working adults with asthma, three experts (one industrial hygienist and two epidemiologists) compared exposure assignments, and modified new JEM based on majority opinion. Modified assignments for 15 detailed and 2 broad occupations.

Table 2.

Description of USA-JEM exposures and comparable N-JEM exposures.

USA-JEM				N-JEM		
Category	**Exposure**	**USA-JEM code**	**Description of exposure/exposed occupations**	**Category**	**Exposure**[a]	**N-JEM code**
LMW agents	Highly reactive LMW agents	ABC	Includes highly reactive chemicals found in resin systems of adhesives, plastics, paints, etc. such as acrylics and acrylates, alkyds, epoxies. Includes amines, aldehydes, anhydrides used in resin systems, and other epoxy resins and associated curing agents (e.g. hardeners, catalysts) and additives. Also includes other LMW reactive chemicals such as styrene and other aromatic hydrocarbons, reactive dyes, persulfates, acids, chlorine gas, chloramines, and chlorine dioxide.	LMW agents	Reactive chemicals (e.g. amines, aldehydes, anhydrides) Acrylates Epoxy compounds	A B C
	(Di) isocyanates	P	Includes MDI, TDI, HDI, and other isocyanate compounds and pre-polymers of diisocyanates.		(Di)isocyanates	P
HMW agents	Animal-derived antigens	H	Includes animal-derived antigens related to agricultural work with animals, including fish and shellfish; work with laboratory animals; and work with other animals, such as domestic pets. Includes animal dander, feathers, urine, and animal-derived dusts. Excludes mites and insects.	HMW agents	Animal-derived antigens, including fish	H
	Plant antigens	I	Examples include flour and cereal associated antigens; grain and grain dust; tobacco; coffee plants and beans; flowers and pollen; fruit; and other HMW plant antigens, such as hops. Excludes latex proteins and organic dusts from wood, paper, and textiles.		Plant-associated antigens from cereal, tobacco, brewery together with mixed agriculture	I
	Latex	D	Latex proteins and antigens. Distinct from “plant antigens.”		Latex protein	D
	Other HMW biological agents	K	Mites, insects, and other arthropod antigens; fungi (e.g. mold, mildew); enzymes; and other bioaerosols not included in categories for animal antigens, plant antigens, and latex. Do not consider exposures related to MWFs in this category; there is a separate category for MWFs.		Arthropod, mite, bioaerosol antigens, antigenic enzyme	K
Mixed agents	Pharmaceutical products (drugs)	S	HMW pharmaceutical product antigens including products with biological enzymes (e.g. papain, pepsin, and ispaghula) and LMW pharmaceutical agents.		Pharmaceutical product antigens	S
	Pest control agents	PEST	Pest control agents including pesticides (e.g. herbicides, insecticides, and fungicides) used primarily for agricultural and structural pest control. Examples of types of pesticides include organophosphates, pyrethrins, and carbamates.	NA	Not a separate category in N-JEM	NA
	Metal working fluids	G	Fluids used to reduce heat and friction, remove particles and debris, and protect work pieces during machining and grinding operations. MWFs include nondiluted straight oils (e.g. castor oil, colophony, pine oil, tall oil), water-based fluids (which support microbial growth including Gram-negative bacterial endotoxins), soluble oils, and semi-synthetic fluids mixed with additives including emulsifiers (e.g. triethanolamine), buffers (e.g. ethanolamine and other amines), anti-weld agents, corrosion inhibitors, biocides (e.g. triazine compounds, formaldehyde), and sulfurized or chlorinated compounds.	Irritant agents	Metal working fluids	G
	Highly reactive disinfectants and sterilants	DIS	Includes agents used in high-level disinfection and sterilization to destroy bacteria and other microorganisms. Examples include glutaraldehyde, orthophthalaldehydes,		Included in cleaning agents	M

USA-JEM				N-JEM		
Category	**Exposure**	**USA-JEM code**	**Description of exposure/exposed occupations**	**Category**	**Exposure**[a]	**N-JEM code**
			formaldehydes, peroxyacetic acid, ethylene oxide, and quaternary ammonium compounds.			
Irritant agents	Cleaning agents	M	Household and professional cleaning agents used primarily for cleaning surfaces. Examples include detergents, soaps, ammonia, and bleach.		Included in cleaning agents	M
	Organic dust, wood	EW	Most wood dusts are irritants, but a few are sensitizing. Sensitizing examples include Western Red Cedar, California Redwood, mahogany, and oak.		Organic dust, wood, paper	E
	Organic dust, paper	EP	Paper dust			
	Organic dust, textile	F	Examples include cotton, wool, synthetic and artificial fibers, linen, jute, silk, and mixtures. (Note: There may be some cases of HMW agent exposure in the earlier processing of natural textile fibers such as cotton or wool)		Organic dust, textile industry	F
	Inorganic dust and fumes, metals	Ometal	Welding, soldering, foundry, manufacturing, electroplating, and other sources of metal fumes and dusts.		Inorganic dust and fumes	O
	Inorganic dust and fumes, multiple sources	Omulti	Exposures related to mining, tunneling, drilling, excavating, building, and construction activities. Includes soil dust, cement dust, mineral fibers (both natural and man-made), and gypsum			
	Second-hand tobacco smoke	N	High probability of exposure to second-hand tobacco smoke		Environmental tobacco smoke	N
	Exhaust and smoke from combustion	L	Vehicle, motor, or generator exhaust, including diesel exhaust, and smoke from fires and other combustion sources.		Vehicle/motor exhaust	L
Peak exposure	Risk of peak irritant exposure	T	Workers in the identified occupations have a greater than normal risk of peak exposure to irritants. (Note: The 50% criterion does not apply to this exposure cat ego ry.)	Accidental peak exposures	Accidental peak exposures	T
NA	NA	NA	NA	Uncertain or low exposed	Uncertain or low exposed	U
Reference group	Reference group	REF	Not exposed to any of the agents	Reference group	Reference group	Z

HMW, high molecular weight; LMW, low molecular weight; Mixed, mixed. HMW and. LMW.

[a]Exposure variable names for the N-JEM are from table 1 in Lillienberg *et al.* (2014).

Table 3.

Number (%) of SOC-2010 detailed occupations in the major occupation groups that have probable or possible exposure to at least one WRA agent in different exposure categories.

SOC-2010 major occupation group code and title	Exposure category						
	N [a]	LMW	HMW	Mixed	Irritants	Peaks	Total
11-0000 Management	34	0	1 (2.9)	1 (2.9)	5 (14.7)	0	5 (14.7)
13-0000 Business and Financial Operations	32	0	0	0	0	0	0(0)
15-0000 Computer and Mathematical	19	0	0	0	0	0	0(0)
17-0000 Architecture and Engineering	35	2 (5.7)	0	0	8 (22.9)	4 (11.4)	10 (28.6)
19-0000 Life, Physical, and Social Science	43	5 (11.6)	9 (20.9)	8 (18.6)	7 (16.3)	3 (7.0)	16 (37.2)
21-0000 Community and Social Service	18	0	1 (5.6)	0	2 (11.1)	0	3 (16.7)
23-0000 Legal	9	0	0	0	0	0	0(0)
25-0000 Education, Training, and Library	63	0	4 (6.3)	6 (9.5)	11 (17.5)	0	14 (22.2)
27-0000 Arts, Design, Entertainment, Sports, and Media	41	1 (2.4)	1 (2.4)	1 (2.4)	3 (7.3)	0	5 (12.2)
29-0000 Healthcare Practitioners and Technical	61	4 (6.6)	43 (70.5)	49 (80.3)	13 (21.3)	5 (8.2)	54 (88.5)
31-0000 Healthcare Support	17	1 (5.9)	11 (64.7)	15 (88.2)	8 (47.1)	1 (5.9)	16 (94.1)
33-0000 Protective Service	22	2 (9.1)	6 (27.3)	3 (13.6)	12 (54.5)	9 (40.9)	17 (77.3)
35-0000 Food Preparing and Serving Related	18	0	2 (11.1)	15 (83.3)	17 (94.4)	0	18 (100)
37-0000 Building and Grounds Cleaning and Maintenance	10	0	6 (60.0)	10 (100)	8 (80.0)	4 (40.0)	10 (100)
39-0000 Personal Care and Service	33	7 (21.2)	7 (21.2)	9 (27.3)	10 (30.3)	1 (3.0)	19 (57.6)
41-0000 Sales and Related	22	0	0	0	2 (9.1)	0	2 (9.1)
43-0000 Office and Administrative Support	56	0	0	0	9 (16.1)	0	9 (16.1)
45-0000 Farming, Fishing, and Forestry	15	0	15(100)	8 (53.3)	11 (73.3)	0	15 (100)
47-0000 Construction and Extraction	60	24 (40.0)	1 (1.7)	3 (5.0)	56 (93.3)	6 (10.0)	58 (96.7)
49-0000 Installation, Maintenance, and Repair	52	16 (30.8)	0	5 (9.6)	19 (36.5)	0	28 (53.8)
51-0000 Production	108	53 (49.1)	17 (15.7)	36 (33.3)	78 (72.2)	15 (13.9)	96 (88.9)
53-0000 Transportation and Material Moving	52	2 (3.8)	1 (1.9)	1 (1.9)	43 (82.7)	1 (1.9)	44 (84.6)
55-0000 Military Specific	20	0	0	0	9 (45.0)	2 (10.0)	9 (45.0)
Total	840	117 (13.9)	125 (14.9)	170 (20.2)	331 (39.4)	51 (6.1)	448 (53.3)

[a] *N* = number of detailed, occupations.

Table 4.

Comparison of exposures assigned by USA-JEM and N-JEM to the current occupations of 557 study participants.

USA-JEM category	Asthma exposure variable[a]	Exposure codes		Number exposed and kappa score		
		USA-JEM	N-JEM	USA-JEM	N-JEM	Kappa
LMW agents	Highly reactive LMW agents, other	ABC	A[b]	18	23	0.52
	Highly reactive agents, acrylates		B[b]			
	Highly reactive agents, epoxy		C[b]			
	(Di) isocyanates	P	P	5	12	0.46
HMW agents	Animal-derived antigens	H	H	5	4	0.44[e]
	Plant antigens	I	I	8	9	0.94[e]
	Latex	D	D	69	56	0.78
	Other HMW biological agents	K	K	5	9	−0.0[c]
Mixed agents	Pharmaceutical products (drugs)	S	S	21	16	0.41
	Pest control agents	PEST	NA	12	NA	NA
	Metal working fluids	G	G	5	12	0.46
	Highly reactive disinfectants and sterilants	DIS[b]	M	146[d]	12	0.10
Irritant agents	Cleaning agents	M[b]				
	Organic dust, wood	EW[b]	E	13	16	0.54
	Organic dust, paper	EP[b]				
	Organic dust, textile	F	F	1	1	NA[c]
	Inorganic dust and fumes, metals	Ometal[b]	O	29	21	0.67
	Inorganic dust and fumes, multiple sources	Omulti[b]				
	Second-hand tobacco smoke	N	N	39	62	0.57
	Exhaust and smoke from combustion	L	L	40	47	0.59
Peak exposure	Risk of peak irritant exposure	T	T	43	6	0.11
Other	Uncertain or low exposed	NA	U	NA	27[e]	NA
	Unexposed	Z	Z	314	303	NA

USA-JEM category	Asthma exposure variable[a]	Exposure codes		Number exposed and kappa score		
		USA-JEM	N-JEM	USA-JEM	N-JEM	Kappa
Any agent	Exposure to any asthma-related agent	Any *probable* exposure	Any *probable* exposure	243	227[e]	0.54

HMW, high molecular weight; LMW, low molecular weight; Mixed, mixed. HMW and. LMW; NA, not applicable.

[a]Most of the variable names and categories are from the USA-JEM. The four that are unique to the N-JEM are three (i.e. highly reactive LMW agents, other; highly reactive agents, acrylates; and highly reactive agents, epoxy) that were combined to form the category for highly reactive LMW agents in the USA-JEM, and the uncertain or low exposed category that is not part of the USA-JEM.

[b]Selected categories were combined to facilitate comparison with the other JEM. The number of participants in the combined categories are presented in the following. From the N-JEM, the participants for categories A = 10, B = 9, and C = 10 accounted for 23 individuals when combined. From the USA-JEM: M = 119 and DIS = 113 accounted for 146 individuals when combined; EW = 7 and EP = 6 accounted for 13 when combined; and Ometal = 21 and Omulti = 18 accounted for 29 individuals when combined.

[c]Fewer than 10 participants assigned exposure by both JEMs.

[d]Only 57 of the 146 had M and/or DIS as their only exposure assigned by the USA-JEM.

[e]For exposures assigned by the N-JEM, the 31 with uncertain exposure and 227 with any exposure had 4 participants in common.

Table 5.

Frequency of *probable* exposure to work-related asthma agents in the 2015 US working population as assigned by the USA-JEM.

USA-JEM category	Work-related asthma exposure	Exposure code	% of workers
Mixed	Highly reactive disinfectants and sterilants	DIS	20.2
Irritants	Cleaning agents	M	17.9
Irritants	Exhaust and smoke from combustion	L	10.7
HMW	Latex	D	10.2
Peak exposure	Risk of peak exposure to irritant	T	8.1
Irritants	Inorganic dust and fumes, multiple sources	Omulti	5.7
LMW	Highly reactive LMW agents, all combined	ABC	4.6
Irritants	Inorganic dust and fumes, metals	Ometal	4.1
Mixed	Pharmaceutical products	S	3.3
Irritants	Second-hand tobacco smoke	N	2.9[a]
HMW	Other HMW biological agents	K	2.5
Mixed	Pest control agents	PEST	1.9
LMW	(Di)isocyanates	P	1.7
Irritants	Organic dust, wood	EW	1.4
HMW	Plant antigens	I	1.2
Mixed	Metal working fluids	G	1.2
Irritants	Organic dust, paper	EP	0.66
HMW	Animal-derived antigens	H	0.61
Irritants	Organic dust, textile	F	0.24
	At least one *probable* exposure		42.6

HMW, high molecular weight; LMW, low molecular weight; Mixed, mixed HMW and LMW.

[a]Median of the agent-specific estimates in this column.