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Original Article

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Development of a Job-Exposure Matrix for Ultrafine Particle Exposure: The MatPUF JEM

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Abstract

Objective: Ultrafine particles (UFPs) are generated from common work processes and have thus existed for a long time. Far more prevalent than engineered nanoparticles, they share common toxicological characteristics with them. However, there is no existing retrospective assessment tool specific to UFPs, for example, for epidemiological purposes. Thus, we aimed to develop a job-exposure matrix dedicated to UFPs.
Method: Fifty-seven work processes were identified as well as the chemical composition of UFPs emitted, following a literature review and the input of an expert panel. These work processes were associated with occupational codes as defined by the ISCO 1968 classification. The probability and frequency of UFP exposure were assessed for each combination of occupational code and process. Summarized probabilities and frequencies were then calculated for all ISCO occupational codes associated with several processes. Variations in exposure over time or across industrial sectors were accounted for in the assessment of each occupational code.
Results: In the ISCO classification, 52.8% of the occupational codes (n = 835) assessed were associated with exposure to UFPs, consisting mainly of carbonaceous, metallic, and mineral families (39.5%, 22 and, 15.8%, respectively). Among them, 42.6% involved very probable exposure, and at a high frequency (regularly or continuously).
Conclusion: These results suggest that occupational exposure to UFPs may be extensive at the workplace and could concern a wide variety of workers. Pending the integration of a third parameter assessing the intensity of UFP exposure, the MatPUF JEM already constitutes a promising and easy-to-use tool to study the possible adverse health effects of UFPs at work. It may also guide

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What's important about this paper?

The toxicity of nanoscale particles is well known. In the workplace, high concentrations of ultrafine particles (UFPs) can be emitted from work processes. The job-exposure matrix called MatPUF is a unique tool for the assessment of occupational UFP exposure that can both contribute to the improvement of epidemiological knowledge of health risks and to the implementation of prevention in the workplace.

prevention policies in the occupational environments concerned, including those involving engineered nanoparticles.

Keywords: exposure assessment; job-exposure matrix; nanoscale particles; occupational exposure; ultrafine particles

Introduction

Several definitions of nanoscale particles have been proposed, but they can be commonly defined as solid particles with at least one dimension in the size range 1–100 nm (Boverhof *et al.*, 2015). In recent years, engineered nanoparticles (ENPs) have been increasingly incorporated into consumer products (cosmetics, paints, sports equipment, drugs, etc.), because of their physicochemical properties, raising the question of the impact on human health due to exposure to such particles (Warheit *et al.*, 2008; Vance *et al.*, 2015). Indeed, toxicological studies have demonstrated that they may have adverse effects on cells and tissues (oxidative stress, genotoxicity, inflammation, fibrosis, etc.) and that they have the capacity to cross biological barriers, including the blood–brain barrier, and are thus able to translocate into several organs (Bakand and Hayes, 2016). Aside from ENPs, other nanoscale particles, generally referred to as ultrafine particles (UFPs) are unintentionally emitted from natural sources (e.g. volcanic eruptions, soil erosion), or widespread technological processes (e.g. diesel engines, welding). Although they may have different characteristics, such as their chemical composition, UFPs and ENPs share one well-known toxicity determinant of nanoscale particles, high surface reactivity (Nel, 2006; Stone *et al.*, 2017). Recent epidemiological studies, mainly of the general environment, strengthen the evidence that UFP exposure plays an important role in cardiovascular diseases, systemic inflammation, respiratory diseases, and cancer (Buonanno *et al.*, 2015; Clifford *et al.*, 2018; Corlin *et al.*, 2018; Downward, 2018). Moreover, the IARC has classified diesel engine exhaust and outdoor air pollution (mainly involving particles from industrial or domestic combustion-based processes) as being carcinogenic to humans (Group 1) (IARC, 2014, 2016). Indeed, UFPs constitute a large numerical fraction of such aerosols and could play an important role in the development of disease, although currently available data are insufficient to draw any strong conclusions (Junker *et al.*, 2000; Du *et al.*, 2012; Ohlwein *et al.*, 2019). In the workplace, numerous industrial hygiene studies now show that UFPs may be generated by various industrial operations (unintentional by-products of processes), suggesting a high prevalence of occupational exposure to UFPs (Elihn and Berg, 2009; Gomes *et al.*, 2012; Debia *et al.*, 2016; Miettinen *et al.*, 2016; Hedmer *et al.*, 2017; Manigrasso *et al.*, 2019). Consequently, UFP exposure should raise at least as many concerns as that to ENPs in terms of worker' health. However, there are currently no practical field recommendations to specifically assess occupational UFP exposure. In most countries, at best, ultrafine particles are included in the assessment to dust exposure or that of exposure to specific chemical substances. In addition, there are no easily implementable exposure assessment methods for epidemiological studies. This may explain the small amount of epidemiological data related to occupational exposure to UFPs and the need to conduct more studies.

Although there are many specific job-exposure matrices (JEMs) concerning various work processes that may entail UFP exposure, there is no tool that exhaustively integrates UFP-emitting activities into a single JEM. In addition, such JEMs do not consider the size of the emitted particles in their assessment. Thus, we aimed to develop a JEM specifically dedicated to exposure to UFPs released from all occupational sources. Here, we describe the construction method and content of the MatPUF JEM, dedicated to occupational UFP exposure.

Method

A JEM provides an estimation of the mean exposure to a given substance for all jobs defined by an occupation and industrial sector. Crossed with individual lifetime job histories, JEMs are an easily implemented assessment tool in epidemiological studies (Kauppinen, 1994). For example, they allow estimating exposure prevalence, highlighting populations at risk, and analysing relationships between exposure and disease (Fevotte *et al.*, 2011).

The MatPUF JEM was constructed by two industrial hygienists between 2010 and 2014. The construction of the JEM was monitored by a multidisciplinary panel of 23 experts (3 aerosol metrologists, 3 chemists, 8 industrial hygienists or risk assessment specialists, 7 occupational physicians and/or toxicologists, and 2 epidemiologists) who together had the necessary specific knowledge to understand UFP exposure assessment. The following seven-step method developed to construct the MatPUF JEM was validated by the expert panel (Table 1).

Step1: Literature search

A literature search was conducted to gather all available information on occupational UFP exposure. Literature data were extracted from two bibliographic databases (PubMed and ScienceDirect) until March 2014, with no restriction on the start date, using a wide-ranging search query: [(nanoparticles) OR (ultrafine AND particles) OR (ultrafine particles) OR (particulate matter) OR (particulate AND matter)]. Scientific articles exclusively targeting ENPs were excluded, as well as those containing no measurements and those targeting non-occupational exposure (unless it could be linked to a similar occupational situation). The results of this literature search were integrated into an open access database called Ev@lutil, which has been continually updated since (Audignon-Durand *et al.*, 2016). Grey literature searches were also conducted (literature not published under peer review, e.g. reports by international research institutes). Following the Ev@lutil methodology, the industrial hygienists extracted the circumstances of exposure at the workplace (work processes, materials, occupations, industries, etc.), the measurement methods used, and the data contained (chemical composition, morphology, size range, concentrations in number, surface, and mass). A standardized analytical grid was thus drawn up and validated by the metrology experts on the panel.

Step 2: Work processes × UFP chemical families

All technological work processes that could have an impact on materials leading to UFP generation were researched. In addition, potential emissions due to the degradation of the materials used in these processes were accounted for (e.g. abrasive discs from machine tools).

UFP-emitting work processes were validated by consensus of the expert panel, which was obtained using Delphi and Nominal Group techniques (Delbecq, 1975; Lindstone and Turoff, 1975). A preliminary list of work processes that potentially emit UFPs was drawn up by the industrial hygienists with the help of the available exposure data gathered during the literature search. This list was sent by email to the experts for their opinion and they were also asked to add work processes to the sent list if necessary. The experts were free to participate and

Table 1. Steps of exposure assessment.

Step	Exposure parameters[a]
1. Work process	Yes/No
2. Work process × occupation	Probability of exposure P_t_i: 0—unexposed, 1 to 10%—possible, >10 to 50%—probable, and >50%—very probable Frequency of exposure F_t_i: 1 to 5%—sporadic, >5 to 30%—occasional, >30 to 70%—regular, and >70%—continuous
3. Occupation[b]	Summarized probability of exposure $\mathrm{P} = 1 - \prod_{i=1}^{number_{work\ processes}} (1 - P\_t_i)$(0—unexposed, 1 to 10%—possible, >10 to 50%—probable and >50%—very probable) Summarized frequency of exposure $\mathrm{F} = 1 - \prod_{i=1}^{number_{work\ processes}} [1 - (P\_t_i \times F\_t_i)]$(1 to 5%—sporadic, >5 to 30%—occasional, >30 to 70%—regular, and >70%—continuous)
4. Temporal axis	Historical period of exposure: start and end years

[a] Estimation per and all UFP chemical families.

[b] Industrial sectors were taken into account for certain occupations.

12 of 23 responded, covering all initial fields of expertise (except epidemiology). The experts' responses were synthesized to highlight discrepancies. The experts were asked to provide their opinion a second time for each discordant point as well as all new work processes proposed by the experts in the first round. Between the first and second rounds, a discrepancy between experts was noted for 45% of the processes, involving 5 of 12 experts. At the end of the second round, there was still disagreement concerning 20% of the processes, involving only three experts. Finally, a meeting was organized with all these experts to validate a final list of work processes that had received the majority of votes. In total, 57 work processes were validated ('MatPUF work processes') and categorized into nine major groups: (i) matter fragmentation, (ii) combustion, (iii) formatting and shaping, (iv) machining, (v) surface treatment, (vi) surface coating, (vii) assembly (welding/thermal cutting), (viii) thermal and electrical engines, and (ix) other work processes not classified elsewhere (see Table S1 in Supplementary data for more details on the 57 work processes).

The experts were also asked to validate the chemical composition of the UFPs emitted for each work process according to the six following chemical families (see Supplementary data Table S2 for more details on the 6 chemical families): (i) metallic particles, (ii) mineral particles, (iii) carbonaceous particles, including solid phase polycyclic aromatic hydrocarbon compounds (PAH particles), (iv) polymer particles (mainly plastic degradation), (v) wood particles, and (vi) other organic particles (e.g. cereals). For each work process, the experts had the choice to link one or more UFP chemical families per process. The chemical families were validated at the same time as the processes according to the same procedure.

Step 3: Association of occupations with work processes

The identified work processes were further associated with occupational codes extracted from the international standard classification of occupations (ISCO edition 1968) (ILO, 1968). This classification describes 1503 occupations defined by a code and a title. Although old, this classification offers the advantage of providing detailed descriptions of tasks, which was essential for associating each occupational code with work processes. Additionally, certain occupational codes integrate information on industrial sectors (e.g. major group 7-3 Wood preparation workers and paper makers or 9-5 Bricklayers, carpenters and other construction workers). In other cases, specific information on industrial sectors had to be considered. Indeed, certain associations between a work process and an occupation were meaningful only in specific industrial sectors. For example, the occupation '8–49.70 - Plant maintenance mechanic' could not be associated with the work process '211 – Furnace' if the information on industrial sector is missing. In such situations, the industrial sectors concerned were specified for each association according to the French classification of industrial activities (NAF edition 2000) (INSEE, 2000), that is '275A - Casting of iron' in this example. An occupation could be associated with one or more work processes based on the usual and principal activity of the workers (up to a maximum of 17 processes for 3 occupational codes).

Step 4: UFP exposure assessment for each 'work process × occupation' association

Two exposure parameters were assessed for each 'work-process × occupation' association: a probability P_t and a frequency F_t of UFP exposure during application of the relevant work process in a given occupation. The probability of exposure assessment resulted from the UFP-release potential of the considered work process (determined from the literature) which was adjusted for each occupation according to the description of tasks and work-processes implemented as provided in the ISCO 1968 classification. The frequency of exposure assessment was based essentially on knowledge of the usual activity in the occupation. Therefore, the probability of UFP exposure for a given work process x occupation association P_t was defined as the proportion of exposed workers in a given occupation that apply the work process in question. The probability was assessed on a four-category scale: unexposed (0), possible (1–10%), probable (>10–50%) and very probable (>50%). The frequency of UFP exposure for a given work process × occupation association F_t was defined as the proportion of working time during which workers were exposed to UFPs due to the application of the work process in a given occupation. The frequency was assessed on a four-category scale: sporadic (1–5%), occasional (>5–30%), regular (>30–70%), and continuous (>70%). This assessment was first independently performed by the two hygienists. They subsequently compared their results and agreed on a final decision for each association. If necessary and in the event of disagreement, specialized experts in industrial hygiene and occupational medicine were asked to decide.

Step 5: Final UFP exposure assessment for each occupation

For occupations associated with one work process, the final exposure parameter assessment was that obtained in the previous step. However, for occupations associated with at least two work processes, an extra step was required to obtain the final exposure parameter assessment. For such occupations, a summarized probability of exposure P and a summarized frequency of exposure F were calculated as follows:

$$P = 1 - \prod_{i=1}^{n} (1 - P\_t_i) \quad F = 1 - \prod_{i=1}^{n} [1 - (P\_t_i \times F\_t_i)]$$

where n is the number of work processes attributed to a given occupation, P_t_i the probability of UFP exposure for the work process i for the given occupation, P the probability of UFP exposure for the given occupation, F_t_i the frequency of UFP exposure for the work process i for the given occupation, and F for frequency of UFP exposure for the given occupation.

As P_t_i and F_t_i were categorical variables, numerical values were attributed to each category and defined as the center of each class to allow this calculation. For the probability of exposure, numerical values were defined as follows: 0.05 – 0.30 – 0.75. For the frequency of exposure F_t, numerical values were defined as follows: 0.025 – 0.175 – 0.50 – 0.85.

These parameters were further categorized into a four-category scale for both the probability of exposure (unexposed, 1 to 10%—possible, >10 to 50%—probable, and >50%—very probable) and the frequency of exposure (1 to 5%—sporadic, >5 to 30%—occasional, >30 to 70%—regular, and >70%—continuous) to facilitate the description of the contents of MatPUF JEM.

Step 6: Temporal axis

Exposure may change over time due to regulations and changes in industrial practices. Thus, a temporal axis was integrated into the JEM, ranging between 1950 and 2014. As there are no specific regulations related to UFPs, only historical periods of changes of work processes were taken into account (e.g. industrial uses of the laser technique were considered by the JEM to have started in 1980 and to have been increasing since 2000). Various values of probability and frequency were assessed according to these changes of use over time. There were as many necessary exposure estimates as there were historical periods (defined by a starting year and an ending year) within the same occupational code.

Step 7: Job exposure assessment by UFP chemical family

All previous assessment steps were also performed by UFP chemical family. A probability and frequency were assessed for each chemical family of UFP identified for each combination between a work process and an occupation. Then, if necessary, they were summarized by occupation according to the previous procedure.

Results

Between 1950 and 2014, more than one of two occupational codes (52.8%) was estimated to have been exposed to UFPs (Table 2): very probably for 35.4% of them, probably for 10%, and possibly for 7.4%. Frequencies attributed to very probable exposure were almost equally distributed across the occasional and regular frequency categories: 12.3 and 13.4%, respectively. Occupational codes for which exposure was probable were associated with sporadic and, mainly, occasional frequency (2.8 and 7.2%, respectively). Otherwise, occupational codes for which exposure to UFPs was possible were all associated with sporadic frequency.

The final JEM contains UFP exposure assessment for all occupational codes as defined by ISCO 1968. For 30 occupational codes, the industrial sector had to be considered, which resulted in 2–6 exposure estimates per relevant occupational code. For 31 occupational codes, historical periods were considered to account for the evolution of industrial practices, which resulted in 2–4 exposure estimates per occupational code.

Consideration of the seven major groups of the ISCO classification resulted in most of the exposed occupational codes being grouped into the major group 7/8/9,

Table 2. Distribution of ISCO occupational codes (N = 1580) according to probability and frequency

ISCO occupational codes, *n* (%)	Frequency									
	Unexposed		Sporadic		Occasional		Regular		Continuous	
Probability										
Unexposed	745	(47.2)								
Possible			117	(7.4)						
Probable			44	(2.8)	114	(7.2)				
Very probable			10	(0.6)	194	(12.3)	212	(13.4)	144	(9.1)

'production and related workers, transport equipment operators and labourers' (*n* = 586) due to the hierarchy of the ISCO classification (Table 3). In this group, exposure for most of the occupational codes was assessed as very probable (46.9%), and on a regular or continuous basis (19.4 and 15%, respectively). As this major group brings together all blue-collar occupations that may require various technical operations in different industrial activities (mining, metallurgy, building construction, etc.), almost all work processes were involved in the assessment of exposure parameters. Group 6, 'agricultural, animal husbandry and forestry workers, fishermen and hunters', regroups 62 exposed occupational codes of 66 in this group (93.9%). In this group, most occupational codes were estimated to be very probably exposed (54 of 62, 87.1%), with a frequency mainly defined as occasional (36 of 54, 66.7%). These codes were assessed as mainly exposed, due to the driving of vehicles and earthworks. Among group 0/1, 'professional, technical and related workers', 33.8% of the occupational codes were assessed to be exposed (123 of 364). Indeed, this group includes engineers and technicians who were mostly indirectly exposed due to the activities of the workers belonging to major group 7/8/9. Consequently, they were also concerned by a large number of work processes and UFP chemical families, and exposure for one of two occupational codes was assessed to as 'possible' or 'probable' (70 of 123, 56.9%). Among group 3, 'clerical and related workers', 11.6% of the occupational codes were assessed to be exposed (10 of 86). This mainly concerned the occupations of mail distribution operators or stock clerks, due to the driving of vehicles (e.g. forklift), or machine operators specialized in printing or photocopying (carbonaceous and metallic particles). Finally, all occupational codes belonging to group 2, 'administrative and managerial workers', were assessed as unexposed.

Concerning the chemical characteristics of UFPs, 88.8% of exposed occupational codes were concerned by between one and three chemical families. Among the six chemical families, the carbonaceous family was the most strongly associated, regardless of probability (39.5%), followed by the metallic and mineral families (22 and 15.8%, respectively) (Table 4). Among the occupational codes for which workers may be exposed to carbonaceous, metallic and mineral particles, 57.3, 75.5, and 65.7% were assessed to be very probably exposed, respectively. Only 75 (4.9%) and 37 (2.5%) occupational codes exposed workers to other organic particles or to polymer particles, respectively. Concerning the seven major groups of the ISCO classification, all (except group 2, which was entirely unexposed) were concerned by exposure to carbonaceous particles (from 62.5% for group 7/8/9 to 1.6% for groups 3 and 4) (Table 5). Otherwise, wood particles were represented in only three major groups (from 84.9% for group 7/8/9 to 6.6% for group 5, which involves textile handling). Finally, polymer particles were characterized in only two major groups, and were due to working with plastics (75.7% for group 7/8/9 and 24.3% for group 0/1).

Discussion

The MatPUF JEM can be used to estimate occupational UFP exposure between 1950 and 2014 through the assessment of occupations as defined by the ISCO 1968 international classification. In total, 52.8% of occupational codes were assessed as leading to occupational UFP exposure, mainly to carbonaceous particles. Exposure was assessed to be very probable, and the frequency to be regular or continuous for 42.6% of the exposed occupational codes.

The MatPUF JEM is the first JEM and the only assessment tool dedicated to occupational UFP exposure. Furthermore, we chose to restrict this tool to UFPs and did not integrate ENPs into the current version of this JEM due to the current socio-economic data available concerning ENPs and their uses in France. A JEM called PARCC JEM was developed to assess exposure to 20 groups of particles based on their origin (e.g. welding fumes, paper dust) (Wiebert *et al*., 2012). Particles exposure was classified into the JEM according to the main particle size released, with a cut-off at 1 µm. Moreover, the experts who built the PARCC JEM considered only combustion processes as sources of submicron particles exposure. Thus, these two JEMs are not comparable and would necessarily produce different results due to a different method of construction.

Applications

Initially, the MatPUF JEM was developed for epidemiological use, providing a standardized and retrospective assessment, that is, less costly and time-consuming than individual expertise (Kromhout, 2001). Although leading to individual-scale classification errors, as JEMs do not take into account inter-individual variability within a homogeneous exposure group (Loomis and Kromhout, 2004), the MatPUF JEM can already provide information on the relationship between occupational UFP exposure and certain health outcomes. However, it requires the coding of the job history of subjects included in epidemiological studies according to the ISCO 1968 classification (and the NAF 2000 for 30 occupations). Once the coding is completed, the MatPUF JEM may be

Table 3. Distribution of ISCO occupational codes according to probability and frequency.

ISCO occupational codes, *n* (%)	Probability															
	Unexposed		Possible		Probable				Very probable							
			Frequency[a]		Frequency[a]				Frequency							
			Sporadic		Sporadic		Occasional		Sporadic		Occasional		Regular		Continuous	
Major group of ISCO classification[b]																
0/1. Professional, technical, and related workers (*N* = 364)	241	(66.2)	25	(6.9)	32	(8.8)	13	(3.5)	8	(2.2)	29	(8.0)	12	(3.3)	4	(1.1)
2. Administrative and managerial workers (*N* = 12)	12	(100.0)														
3. Clerical and related workers (*N* = 86)	76	(88.4)	3	(3.4)	1	(1.2)	5	(5.8)			1	(1.2)				
4. Sales workers (*N* = 32)	22	(68.8)	1	(3.1)			3	(9.4)			6	(18.7)				
5. Service workers (*N* = 94)	50	(53.2)	23	(24.5)	7	(7.4)	2	(2.1)	2	(2.1)	6	(6.4)	4	(4.3)	.	.
6. Agricultural, animal husbandry and forestry workers, fishermen, and hunters (*N* = 66)	4	(6.1)	1	(1.5)	1	(1.5)	6	(9.1)			36	(54.5)	17	(25.8)	1	(1.5)
7/8/9. Production and related workers, transport equipment operators, and labourers (*N* = 926)	340	(36.7)	64	(6.9)	3	(0.3)	85	(9.2)			116	(12.5)	179	(19.4)	139	(15.0)
All occupational codes (*N* = 1580)	745	(47.2)	117	(7.4)	44	(2.8)	114	(7.2)	10	(0.6)	194	(12.3)	212	(13.4)	144	(9.1)

[a] Not presented: empty cells corresponding to other frequency categories.

[b] Major groups as defined in the ISCO classification.

Table 4. Distribution of ISCO occupational codes according to probability and UFP chemical family.

	UFP chemical family											
	Metallic		Mineral		Carbonaceous		Polymer		Wood		Other organic	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%
Probability												
Unexposed	1190	78.0	1291	84.2	952	60.5	1476	97.5	1367	90.0	1439	95.1
Possible	30	2.0	39	2.5	125	8.0	4	0.3	43	2.8	12	0.8
Probable	52	3.4	44	2.9	140	8.9	4	0.3	45	3.0	59	3.9
Very probable	253	16.6	159	10.4	356	22.6	29	1.9	64	4.2	4	0.2
Total[a]	1525	100.0	1533	100.0	1573	100.0	1513	100.0	1519	100.0	1514	100.0

[a] One to several chemical families may have been assigned to the same occupational code and also one to several estimates by account for variations in exposure due to historical periods and industrial sectors.

linked to the jobs of subjects and the exposure parameters automatically assigned to each job. The choice of the ISCO 1968 classification was guided by the detailed description of activities provided for each occupational code. Indeed, although it is an old classification, it offers sufficient detail concerning the description of tasks and work processes to be able to link defined UFP-emitting work processes to occupational codes with good precision. In contrast, exposure due to certain recent working conditions or processes could be assessed more specifically with newer classification editions. In this respect, MatPUF JEM has already been used in epidemiological studies and has made it possible to highlight a relationship between occupational exposure to UFPs and small for gestational age and, cancers, such as lung cancer and brain nervous system tumours (Manangama *et al.*, 2019, 2020).

For further studies, our work may provide useful documentation to design task-based questionnaires drawing on MatPUF JEM work processes (Sauve and Friesen, 2019). It may also motivate investigations into specific occupational groups of interest, highlighted by their occupational exposure assigned by the MatPUF JEM (Kauppinen *et al.*, 2014).

Moreover, MatPUF JEM may also be used to refine the study of the relationship between exposure to ENPs and health effects. Indeed, except in clean rooms, workers involved in ENP activities are also exposed to UFPs, which make up the background aerosol. Although the MatPUF JEM does not assess UFPs from outdoor air infiltration, this tool allows consideration of those emitted by nearby workstations. Considering exposure to UFPs therefore appears to be essential for properly assessing the contribution of ENPs to health outcomes (Ono-Ogasawara, 2009; Guseva *et al.*, 2015). Finally, from the perspective of prevention, the MatPUF JEM is an immediately operational tool to help identify potentially at-risk situations without waiting for more consolidated epidemiological data. In this context, the MatPUF JEM can provide indications to alert users to the risk of UFP exposure related to certain work situations through the list of exposed occupations or work processes. It can also contribute to improving air quality in the indoor environment by highlighting UFP-emitting processes common to the workplace (e.g. cooking, use of electrically powered devices, do-it-yourself work). However, JEMs do not replace the analysis of each particular situation by prevention professionals. The MatPUF JEM can be made available upon request to the authors.

Expert judgment

Although certain JEMs have been built using existing measurement databases, others, such as the MatPUF JEM, are based on expert judgment through the knowledge of experts and available bibliographic information on UFPs (Orlowski *et al.*, 1993; Kennedy *et al.*, 2000; Dopart and Friesen, 2017). In the absence of information, experts rely on their sound knowledge of occupational activities (materials, work processes, etc.) and similar documented situations (estimation by analogy). The construction of the MatPUF JEM quite originally relies on a well-formalized protocol based on a structured consensus technique. In addition, the involvement of a large number of experienced and multidisciplinary experts in the development of the protocol and directly in the assessment steps reinforces the reliability of the JEM. Each step in the assessment was validated through consensus techniques. Step 2 was validated according to a consensus technique that integrated the experts' opinions in the assessment process. Step 4 was validated through a double assessment of exposure parameters by two industrial hygienists, with the involvement of specialized experts in the event of discrepancies. Moreover, the literature search that we performed (and which is still ongoing) is a major strength in the building of the MatPUF JEM. First, it allowed the hygienists involved in the development of this JEM to improve their level of expertise concerning UFP exposure. Second, it permitted the establishment of a preliminary list of UFP-emitting work processes and to make strong hypotheses by analogy of other work processes that were less well documented in the literature. Thus, it allowed us to exhaustively identify UFP-emitting work processes. Third, at the beginning of this initiative, we intended to document an intensity of exposure parameter based on quantitative measurement data gathered from the literature. This would have not been possible based on the expert judgment alone. However, once the measurement data were compiled, the heterogeneity of the data did not allow us to estimate this parameter. These last two points were the motivation to set up the ExproPNano project, which aimed to provide a practical field measurement strategy to assess UFP and ENP exposure. Based on a transdisciplinary approach that crossed aerosol measurement and ergonomic work analysis under real and complex conditions, more and relevant exposure data were produced and typical situations of exposure and their determinants in real conditions were identified (Galey *et al.*, 2020).

Nonetheless, the MatPUF JEM was not externally validated following the usual procedures. Indeed, a comparison of the results obtained with the MatPUF JEM and other evaluation methods, such as the individual assessment of occupational histories extracted from various studies, would have made it possible to assess its performance (sensitivity/specificity) (Benke *et al.*, 2001; Bhatti *et al.*, 2011; Kurth *et al.*, 2017). In our project, the experts who contributed to the construction of the JEM were the same as those who conducted the assessment. Thus, the agreement analysis may have been biased due to a high correlation. Moreover, there is currently insufficient evidence to validate the JEM through known associations between occupational UFP exposure and diseases.

Table 5. Distribution of exposed ISCO occupational codes according to UFP chemical family.

	UFP chemical families											
	Metallic		Mineral		Carbonaceous		Polymer		Wood		Other organic	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%
Major group of ISCO classification[a]												
0/1. Professional, technical, and related workers	62	18.5	55	22.7	118	19.0	9	24.3	13	8.5	4	5.3
3. Clerical and related workers	5	1.5			10	1.6						
4. Sales workers					10	1.6						
5. Service workers	6	1.8	2	0.8	34	5.5			10	6.6	7	9.3
6. Agricultural, animal husbandry and forestry workers, fishermen, and hunters			34	14.0	61	9.8					12	16.0
7/8/9. Production and related workers, transport equipment operators, and labourers	262	78.2	151	62.5	388	62.5	28	75.7	129	84.9	52	69.3
All exposed occupational codes	335	100.0	242	100.0	621	100.0	37	100.0	152	100.0	75	100.0

[a] Major groups as defined in the ISCO classification.

Exposure parameters

The MatPUF JEM provides information about the chemical composition of the UFPs. Although UFPs share common toxicity properties, some may be more or less biologically active depending on their chemical composition (Stone, 2017). Indeed, the surface reactivity may differ from one chemical species to another or their polyatomic organization (crystallographic structure versus amorphous state), thus modifying their surface reactivity from one particle to another (Oberdorster *et al*., 2005). Moreover, certain particles, such as metals, may induce cell injury through two major mechanisms: (i) the generation of ROS and oxidative stress for redox active metals such as Fe, Ni, and Cu, and/or (ii) the induction of an inflammatory response to partially soluble non-redox metals that release ions (Lu *et al*., 2015). Functional groups such as carboxylic acid may exist on the surface of carbonaceous particles increasing their ability to act as a carrier for other species such as cations modifying their surface properties (Pattammattel *et al*., 2019). The proposed chemical classification with six families is based on the main chemical classes according to their origin, independently of their intrinsic toxicity. However, the main interest of such categorization in the epidemiological application of such JEMs (Manangama, 2020) is to identify differential risk assessment to justify further research on toxicological mechanisms.

UFP exposure is documented through two parameters: a probability and a frequency. This is better than a dichotomous evaluation. However, when the MatPUF JEM protocol was drawn up, we intended to include an estimated intensity of exposure parameter. However, upon completing the literature review, we noted that the collected measurement data did not cover all occupational situations and 42% (N = 24) of the work processes identified were not documented (Supplementary data Table S3, available at *Annals of Occupational Hygiene* online). In addition, when measurement data were available (mainly for combustion-based processes, operations on metals and combustion engines), we were confronted with the heterogeneity of these data in terms of the measurement methods used (strategy and type of instruments), as recently and extensively reported in a literature review (Viitanen, 2017). This analysis confirmed the difficulties encountered in measuring nanoscale particles (Witschger, 2011) and we decided not to use the collected measurement data in their current state (aggregation of data, comparison, etc.). Consequently, it was not possible to assess the levels of UFP emission by work processes with sufficient reliability to estimate a final intensity of exposure parameter by occupation.

The absence of such intensity of exposure parameters makes the MatPUF JEM less specific to UFP exposure, even though the MatPUF JEM considers work activities that entail UFP exposure. However, as there are no work activities that specifically entail UFPs, exposure to larger particles is also indirectly considered. The present version of the MatPUF JEM integrates published data until 2014. However, all data published since 2014 relative to occupational exposure to ultrafine particles are collected and integrated into the Ev@lutil database (https://ssl2.isped.u-bordeaux2.fr/eva_003). The impact of the last 6 years of published data, which were not integrated into the MatPUF JEM, should be limited, as there are no intensity parameters in the current version of the JEM and no additional work activities entailing occupational UFP exposure were identified. At best, some of the already identified work activities were better documented.

We are now working on an update of the MatPUF JEM that takes into account all currently available measurement data to overcome the aforementioned limitations. Our intention is to build a dynamic JEM that will integrate additional exposure parameters for each work process, depending on the state of the available data or the use of the JEM (epidemiology or prevention). Specifically, we are working on a method that will allow us to assess exposure intensity parameters either qualitatively or quantitatively according to the available data. We are also planning to integrate an additional exposure parameter that will document the proportion of UFPs in aerosols to discriminate exposure to ultrafine particles from that of larger particles. Finally, we plan to integrate more detailed information concerning industrial sectors to better account for indirect or ambient exposure. This should preferably be carried out using recent job classifications. Analyses could be carried out to assess the consequences of using one edition of the classification compared to another for the estimation of occupational UFP exposure.

Conclusion

A large number of workers was/is still concerned by UFP exposure, and the current version of the MatPUF JEM already constitutes a very relevant and easy-to-use tool for epidemiological purposes. It may also contribute to better prevention for workers concerned by the risk of exposure to nanoscale particles, whether unintentional or engineered.

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Conflict of interest

The authors declare that they have no conflict of interest.

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