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Lifetime occupational exposure proportion estimation methods: a sensitivity analysis in the general population

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Abstract

Objective To present a sensitivity analysis of the most widely used means of estimating lifetime occupational exposure proportion (LOEP) and their respective impacts on LOEP and population-attributable fraction (PAF) estimates.

Methods A French population-based sample with full job history ($N = 10,010$) was linked with four Matgéné job-exposure matrices: flour, cement, silica and benzene. LOEP and the 95% confidence interval were estimated using four methods: the maximum exposure probability during the career (Proba_max), two methods subdividing careers into job-periods (job-period_M1, job-period_M2) and one into job-years (job-year). To quantify differences between methods, percentages of variation were calculated for proportion values and PAF, and compared with published results for France using cross-sectional proportion multiplied by a factor.

Results For each agent, LOEP estimated from the maximum probability during the career (Proba_max) was consistently lower than proportion taking account of job-periods or job-years. LOEP on Proba_max for flour, cement, silica and benzene were, respectively, 4.4% 95% CI (4.0–4.7), 4.3% (3.9–4.6), 6.1% (5.7–6.5) and 3.9% (3.6–4.2). Percentage of variation ranged from 0 to 55.8% according to the agent. The number of cancer cases varied by a twofold factor for exposure to silica and lung cancer and by a fourfold factor for exposure to benzene and acute myeloid lymphoma.

Conclusions The present study provides a description of several LOEP estimation methods based on exposure assessment over the entire career and describes their impact on PAF. For health monitoring purposes, we recommend to report a range of LOEP with low and high estimates obtained using job-periods (job-period_M1 and job-period_M2).

Keywords Job-exposure matrix (JEM) · Lifetime occupational exposure proportion · Prevalence · Population-attributable fraction (PAF) · Statistical method

Introduction

Occupational risk exposure assessment is a major issue in public health surveillance. People spend about half their lives at work, where they may be exposed to a number of substances, some of which can be carcinogenic.

To quantify the number of workers or retirees exposed to occupational hazards, exposure prevalence is often used by estimating the proportion of occupationally exposed individuals in a given population including active workers, retirees, unemployed or inactive workers. However, to estimate the burden of disease through the estimation of attributable fraction to occupational exposure of a given disease, exposure prevalence needs to take account of lifetime occupational exposure, which involves assessing exposure over a person's entire career, whether exposure is ongoing or not (Gilg Soit Ilg et al. 2015, 2016; Hutchings and Rushton 2012; Pukkala et al. 2005; Sundstrup et al. 2017). It is particularly important in the case of diseases with long latencies, which may be as much as 30 or 40 years in certain cancers such as exposure to asbestos and the onset of mesothelioma.

Occupational exposure assessment is complex and often requires precise expertise, as workers are rarely aware of the occupational risks to which they are exposed. Exposure has to be ideally assessed for each job throughout

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each individual's careers to estimate lifetime occupational exposure proportion (LOEP) to a specific agent, which is defined as the percentage of workers in the population studied who have been exposed to the specific agent at least once in their career. However, this is not always feasible due to lack of information and several methods can be used to document LOEP but none has been identified as a gold standard. In large population-based studies, two different approaches are used; (i) when occupational history is available, LOEP can be estimated by crossing population-based job-exposure matrices (JEM) with occupational histories, which enables average assessments of occupational exposure (exposure probabilities, exposure level or frequency) per job and per exposure period for all subjects (El Yamani et al. 2018; Fevotte et al. 2011), (ii) when the occupational history is not available, LOEP can be obtained using occupational exposure proportion for a given year multiplied by a factor (Hutchings and Rushton 2012; Marant Micallef et al. 2018b). In the latter, the occupational exposure proportion can be obtained through occupational exposure surveys or using JEMs merged with population data such as census data (Béryl Matinet et al. 2020; Kauppinen et al. 2014).

There have been few reports of proportion of occupational exposure over entire careers and moreover using population-based job-exposure matrices as exposure assessment (Boffetta et al. 2010; Imbernon 2001). The method used to obtain LOEP with occupational exposure over entire careers are rarely described in detail and several methods can be used. Those methods and their impact on LOEP estimates and, therefore, on the estimation of population-attributable fraction (PAF) have at our knowledge never been studied.

The aim of this study is to present a sensitivity analysis of the most widely used statistical approaches to estimate lifetime occupational exposure proportion, when occupational exposure over the entire career is available, and their respective impacts on LOEP and PAF estimates and compare those results to previous published results for French population using occupational exposure prevalence for a given year multiplied by a factor.

Materials and methods

Estimating LOEP in a given population requires a study sample with job information and exposure data. The studied sample may be a representative sample of the general population including active workers and former workers (retirees, unemployed, inactive workers) or a specific population such as retirees or construction workers for example.

Study sample

In 2007, a sample of individuals' representative of the French population was constituted by random quota selection from the telephone directory (Fevotte et al. 2011). This sample was created specifically to obtain career history of French people representative of the French general population, including workers, unemployed, retirees and inactive individuals, to use population-based job-exposure matrices and estimate lifetime occupational exposure proportions. Quotas were based on the 1999 French national census (Insee 2002), last census available at the time, in terms of age, gender, socio-occupational category and geographical region. To validate our sampling approach, the population distribution using the same quotas variables were compared to the 2007 French Labour Survey (Insee 2008). During telephone interviews, sociodemographic data and career history were collected. Jobs defined by occupation performed in an industry sector were coded according to national and international classifications. Occupation codes were based on the 1982 French occupational and socio-occupational classification ("Professions et Catégories Socioprofessionnelles", PCS) (Insee 1994) and 1968 International Standard Classification of Occupations (ISCO) (ILO 1968). Industries were coded using the 1993 French economic activities classification ("Nomenclature d'Activités Française", NAF) (Insee 1999) and the 1975 International Standard Industrial Classification (ISIC) (United Nations 1975). The sample comprised 10,010 subjects, aged 25–74 years (4758 men, 5252 women) and 28,188 jobs (i.e., a mean of 2.8 jobs per person).

Exposure assessment

Job-exposure matrices

Exposure was assessed using job-exposure matrices (JEM) developed in the framework of the Matgéné program (Fevotte et al. 2011) by expertise through a team of industrial hygienists to exhaustively describe occupational exposures since the 1950s in France. They are based on identification of situations of occupational exposure to a specific agent, associated metrology retrieved in the literature and changes in French regulations (Fevotte et al. 2006, 2011). A JEM is a database crossing for each potentially exposed job, exposure indices by historical periods: probability, intensity, frequency or level of exposure (Table 1). Exposure probability is defined as the proportion of exposed workers in the job over a given period. Intensity is considered as the mean of the exposure intensities of all

Table 1 Extract from ISCO 1968 × NAF 1993 benzene matrix

ISCO 1968 code	ISCO 1968 job title	NAF 1993 code	NAF 1993 industry	Period	Probability (%)	Intensity (ppm)	Frequency (%)
0-11.10	Chemist in general	23.1Z	Coking	1947–1969	10–50	5–15	30–70
0-11.10	Chemist in general	23.1Z	Coking	1970–1988	10–50	1–5	5–30
0-11.10	Chemist in general	23.1Z	Coking	1989–2005	10–50	0.1–1	5–30
0-11.10	Chemist in general	24.1G	Production of other basic organic chemical products	1947–1969	10–50	1–5	5–30
0-11.10	Chemist in general	24.1G	Production of other basic organic chemical products	1970–1985	10–50	0.1–1	5–30
0-11.10	Chemist in general	24.1G	Production of other basic organic chemical products	1986–2005	1–10	0.1–1	0.5–5
0-11.10	Chemist in general	73.1Z	R&D in physical and natural sciences	1947–1969	10–50	1–5	0.5–5
0-11.10	Chemist in general	73.1Z	R&D in physical and natural sciences	1970–2005	1–10	0.1–1	0.5–5

From: Pilorget et al. (2007)

To read the table: an individual who has worked as a chemist in general (0–11.10) in the coking industry (23.1Z) between 1947 and 1969, has an exposure probability comprised between 10 and 50%, an intensity comprised between 5 and 15 ppm and had been exposed between 30 and 70% of the time

at-risk tasks performed in the job. Frequency is described as the mean percentage time of exposure during such tasks. Finally, exposure level combined intensity and frequency. Each index is assessed on a scale which is specific for each JEM (Table 2). One exposure period for a given job with a single assessment in the matrix is known as a job-period. Likewise, exposure assessment for a given job for a given year is known as a job-year. For example, in Fig. 1, the job n°2 with a work period from 1966 to 1971 is divided into two job-periods, one from 1966 to 1969 and a second one from 1970 to 1971 with two different exposure probability assessments. The same job would be divided into six job-years, one for each year between 1966 and 1971. Although, the intensity and frequency are not used specifically in the LOEP calculation, those indices are important in the grouping used in the method described later on. The Matgéné JEMs are available with various national and international job classifications. The ISCO 1968 × NAF 1993 version was used here, being the most accurate in terms of occupations and industries, with about 1500 codes for the ISCO and 700 for the NAF. In the aim of our study, four agents were selected from the 27 Matgéné JEMs: flour dust, cement dust, alveolar dust of free crystalline silica (silica dust) and benzene. They were chosen according to various criteria. First, they were different agent's types: organic dust for flour, mineral dust for cement and silica, and solvents for benzene. Second, these JEMs had particular characteristics according to the agent of interest which could impact proportion estimates (Table 2). One difference was the number of periods assessed in each matrix: the flour matrix is comprised of just one exposure period, while cement dust had three and silica dust and benzene had several distinct periods according to the industry and/or product causing the agent exposure (such as a specific period for mines and quarries in the silica dust JEM or a specific period for the use of gasoline in the benzene JEM). Another difference lay in the exposure probability for three of the agents (flour dust, cement dust and benzene), with a 4-category probability scale; whereas, the silica dust matrix had a 10-category scale. Another difference concerned intensity and frequency: the cement dust, silica dust and benzene matrices assessed intensity and frequency separately; whereas, the flour matrix assessed only an exposure level, combining intensity and frequency. These agents were also selected due to their importance in the public health context, some are known carcinogenic such as benzene and silica which are classified as group 1 by the International Agency for Research on Cancer (IARC) (International Agency for Research on Cancer 2020), some are risk factors for respiratory disease such as exposure to flour and onset of asthma (Zhang et al. 2019), and some have different prevalence trend over time, such as benzene with decreasing exposure over time or silica and cement with relatively stable occupational exposure proportions.

Application of JEMs to the study sample

To estimate lifetime occupational exposure, defined as the percentage of individuals who have been exposed at least

Table 2 Job-exposure matrices characteristics

Matrix characteristics	Flour dust	Cement dust	Benzene	Silica dust
Exposure periods	1950–2005	1945–1969	Gasoline	Mines
		1970–1984	1947–1988	1947–1960
		1985–2005	1989–2005	1961–1980
				1981–2007
			Preparations containing benzene	Quarries
			1947–1969	1947–1960
			1970–1985	1961–1995
			1986–2005	1996–2007
			+ Specific periods in certain industries	Industry and construction
				1947–1970
				1971–1985
				1986–1998
				1999–2007
Exposure probability	1–10 %	1–10 %	1–10 %	1–5 %
	10–50 %	10–50 %	10–50 %	5–10 %
	50–90 %	50–90 %	50–90 %	10–20 %
	90–100 %	90–100 %	90–100 %	20–30 %
				…
				90–100 %
Exposure intensity[a]	< 2.5 mg/m^3	0.1–0.3 mg/m^3	0.1–1 ppm	0.02–0.1 mg/m^3
	2.5–5 mg/m^3	0.3–1 mg/m^3	1–5 ppm	0.1–0.5 mg/m^3
	5–10 mg/m^3	1–2.5 mg/m^3	5–15 ppm	0.5–1 mg/m^3
	10–20 mg/m^3	2.5–5 mg/m^3	≥ 15 ppm	≥ 1 mg/m^3
		≥ 5 mg/m^3		
Exposure frequency[a]		1–5 %	0.5–5 %	1–5 %
		5–30 %	5–30 %	5–10 %
		30–70 %	30–70 %	10–20 %
		70–100 %	70–100 %	20–30 %
				…
				90–100 %

[a]For flour dust, exposure level combines frequency and intensity

once in their career, the job histories of the study sample had to be linked with the JEMs. This is done using the ISCO occupational classification code and NAF industry classification code and the occupational period, as shown in Table 1. For example, a job may belong to two different exposure periods in the matrix, in which case it is divided into two job-periods with starting and finishing dates taking account of the occupational period and the exposure period (Fig. 1).

For the flour, cement and benzene matrices, where assessments ended in 2005, the indices of the last exposure period were used for exposure in 2006 and 2007, after checking that there was no particular change in regulations or other major changes for these exposures in France during this period.

Estimation of lifetime occupational exposure proportion (LOEP) when occupational history is not available

When job histories are not available, the LOEP can be estimated using a proportion of workers exposed for a given year multiplied by a factor. The International Agency for Research on Cancer has used this method in particular to estimate the Global Burden of Disease of occupational exposure in France in 2007 and 2018. The 2007 IARC

Job history of person X

	Work period	Occupation (ISCO 1968)	Industry (NAF 1993)
Job n°1	1960-1965	0-11.50	24.6E
Job n°2	1966-1971	0-11.10	24.3Z
Job n°3	1972-1985	0-11.50	73.1Z
Job n°4	1986-1999	0-11.50	23.1Z

Occupation (ISCO 1968)	Industry (NAF 1993)	Exposure period	Probability	Intensity	Frequency
0-11.10	24.3Z	1947-1969	4	3	4
0-11.10	24.3Z	1970-1985	3	1	2
0-11.50	23.1Z	1947-1969	2	3	3
0-11.50	23.1Z	1970-1988	2	2	2
0-11.50	23.1Z	1989-2005	2	1	2
0-11.50	24.6E	1947-1969	2	4	3
0-11.50	24.6E	1970-1994	2	2	2
0-11.50	24.6E	1995-2005	1	1	2
0-11.50	73.1Z	1947-1969	2	2	1
0-11.50	73.1Z	1970-2005	1	1	1

Linking benzene matrix with job history

		Exposure period	Occupation	Industry	Probability	Intensity	Frequency
Job-period n°1	Job n°1	1960-1965	0-11.50	24.6E	2	4	3
Job-period n°2	Job n°2	1966-1969	0-11.10	24.3Z	4	3	4
Job-period n°3	Job n°2	1970-1971	0-11.10	24.3Z	3	1	2
Job-period n°4	Job n°3	1972-1985	0-11.50	73.1Z	1	1	1
Job-period n°5	Job n°4	1986-1988	0-11.50	23.1Z	2	2	2
Job-period n°6	Job n°4	1989-1999	0-11.50	23.1Z	2	1	2

Lifetime exposure probability attributed to person X on the various methods: *(calculation uses mean class centers: 1=5%, 2=30%, 3=70%, 4=95%).*
Proba_max: probability=95%
Job-period_M1: probability=1−[(1−0.3)x(1−0.95)x(1−0.7)x(1−0.05)x(1−0.3)]=99.3%
Job-period_M2: probability=1−[(1−0.3)x(1−0.95)x(1−0.7)x(1−0.05)x(1−0.3)x(1−0.3)]=99.5%
Job-year: probability=1−[(1−0.3)^{6}x(1−0.95)^{4}x(1−0.7)^{2}x(1−0.05)^{14}x(1−0.3)^{3}x(1−0.3)^{11}]=100%

Fig. 1 Fictional example of benzene job-exposure matrix applied to a job history

method used the proportion of exposed workers from the 1994 SUMER occupational exposure survey and a factor three (International Agency for Research on Cancer 2007). The 2018 IARC method used the proportion of occupationally exposed individuals from the 2003 SUMER survey and a specific age–gender factor (International Agency for Research on Cancer 2018). The 1994 and 2003 SUMER surveys did not have the same target population. In 1994, the survey included only workers from the private sector, as in 2003, some workers from the public service such as workers in hospital have been included. Therefore, we decided to apply the 2007 IARC method (prevalence multiplied by a factor 3) on the 2003 SUMER prevalence to be more comparable between the two IARC methods.

Estimation of lifetime occupational exposure proportion (LOEP) using occupational history

Probability of exposure in a JEM being defined as the proportion of exposed workers in the job over a given period, population-based LOEP is estimated from the mean individual exposure probability, which is obtained by taking account of assessment for each job composing the individual's career. The LOEP is then obtained, as:

$$\text{Proportion} = \sum_{i=1}^{N} \frac{\text{Pind}_i}{N}, \tag{1}$$

where Pind_i: individual exposure probability of each individual i. N: total number of individuals in the sample.

This individual exposure probability (Pind_i) can be obtained by several methods when using job-exposure matrices, all based on the individual's job-exposure probabilities given by the matrices. Among the four methods presented below (Supplement I), one method took account of the maximum exposure probability during the career (Proba_max), three used individual exposure probabilities, two of which subdivided careers into job-periods (job-period_M1 and job-period_M2) and one which subdivided careers into job-years (job-year). For each method, LOEP was estimated for the entire sample.

Maximum exposure probability during the career (Proba_max)

In the first method, the individual is attributed the maximum probability occurred over his or her career for a specific agent. Each job-period assessed in the matrix

is analyzed, and the individual is attributed the highest exposure probability found (Fig. 1). Individuals with no exposed jobs had a probability of 0.

Individual exposure probability based on subdividing the career into job-periods (job-period_M1 and job-period_M2)

The other two methods took account of exposure associated with each job-period, by linking the career and the matrices assessments. This method took account of changes in occupational practices and regulations, and hence exposure, over time.

Job-period_M1 grouped together all the individual's consecutive job-periods with the same estimated probability, the remaining indices (frequency, intensity and level) being free to vary. This method minimized the number of job-periods per person. For example, if we considered job n°4 in Fig. 1, this job would be counted as only one job-period as the exposure probability is the same from 1986 to 1999.

Job-period_M2 grouped together job-periods having the same global exposure on all JEM indices: probability, frequency, intensity or level. This method took greater account of change in exposure indices over time, especially regarding intensity and frequency. If we continued to consider job n°4, in this scenario, this job would be divided into two job-periods, although the exposure probability is the same, the intensity of exposure had changed in 1989 due to French regulations.

With these two methods, individual exposure probability is calculated on the assumption that job-period exposure' assessments are independent, using the following formula:

$$\text{Pind}_i = 1 - \prod_{j=1}^{J} \left(1 - p_j\right), \tag{2}$$

where: Pind_i: individual exposure probability for individual i. p_j: exposure probability for job-period j for method job-period_M1 and job-period_M2 or job-year j for method job-year (see "Individual exposure probability estimated by career cut into job-years (job-year)"). j: individual's number of job-periods or job-years according to the method used for individual i.

Thus, LOEP is calculated as the mean of the individual probabilities and obtained using the formula (1).

An example of the calculation for method job-period_M1 and job-period_M2 is presented in Fig. 1.

Individual exposure probability estimated by career cut into job-years (job-year)

The method job-year broke the career down by years of exposure (job-years), whatever the matrix assessment. As an example, when considering job n°4 in Fig. 1, this job would be divided in 14 job-years, for each year of the job. This method presupposed that JEM exposure estimates were per one working year. Individual exposure probability is, thus, calculated from these job-years using formula (2) replacing "job-period" by "job-year", assuming exposure assessment for each job-year to be independent. LOEP is then calculated as the mean of the individual probabilities obtained using formula (1).

Comparison of LOEP and PAF according to method

LOEP was estimated on the study sample for each of the above methods for the four agents assessed by the Matgéné JEMs and 95% confidence intervals were estimated by the bootstrap method (Efron and Tibshirani 1986). All analyses were performed using Stata 2013 software (Stata Statistical Software: release 13. StataCorp LP, College Station, TX).

To quantify differences between methods, percentage of variations were calculated for proportion values estimated with different methods (IARC methods, job-period or job-year method) versus Proba_max as reference. The Proba_max method was chosen as reference because it took into account all the exposure appeared during the career compared to an estimation of the lifetime exposure based on the SUMER prevalence where the exposure is only assessed on the week prior the interview.

Then, to observe the impact of LOEP estimation methods on PAF estimates, PAF in 2017 were calculated for the agent–cancer site, silica–lung cancer and PAF in 2007 for the pair benzene–acute myeloid leukemia (AML), using the six LOEP estimation methods and the RR published by IARC in 2018 based on the Levin formula (Levin 1953):

$$\text{PAF} = \frac{P_L(RR - 1)}{1 + P_L(RR - 1)},$$

where P_L is the lifetime prevalence of exposure to each agent, and RR is the relative risk linking each occupational agent to a cancer site (Marant Micallef et al. 2018a). The PAF for the pair benzene–AML was calculated for the year 2007 due to the short latency period for hematopoietic cancers (exposure in the last 20 years prior the cancer). The incident number of cancer cases in 2007 for AML and in 2017 for lung cancer was obtained through e-cancer.fr (Defossez 2019).
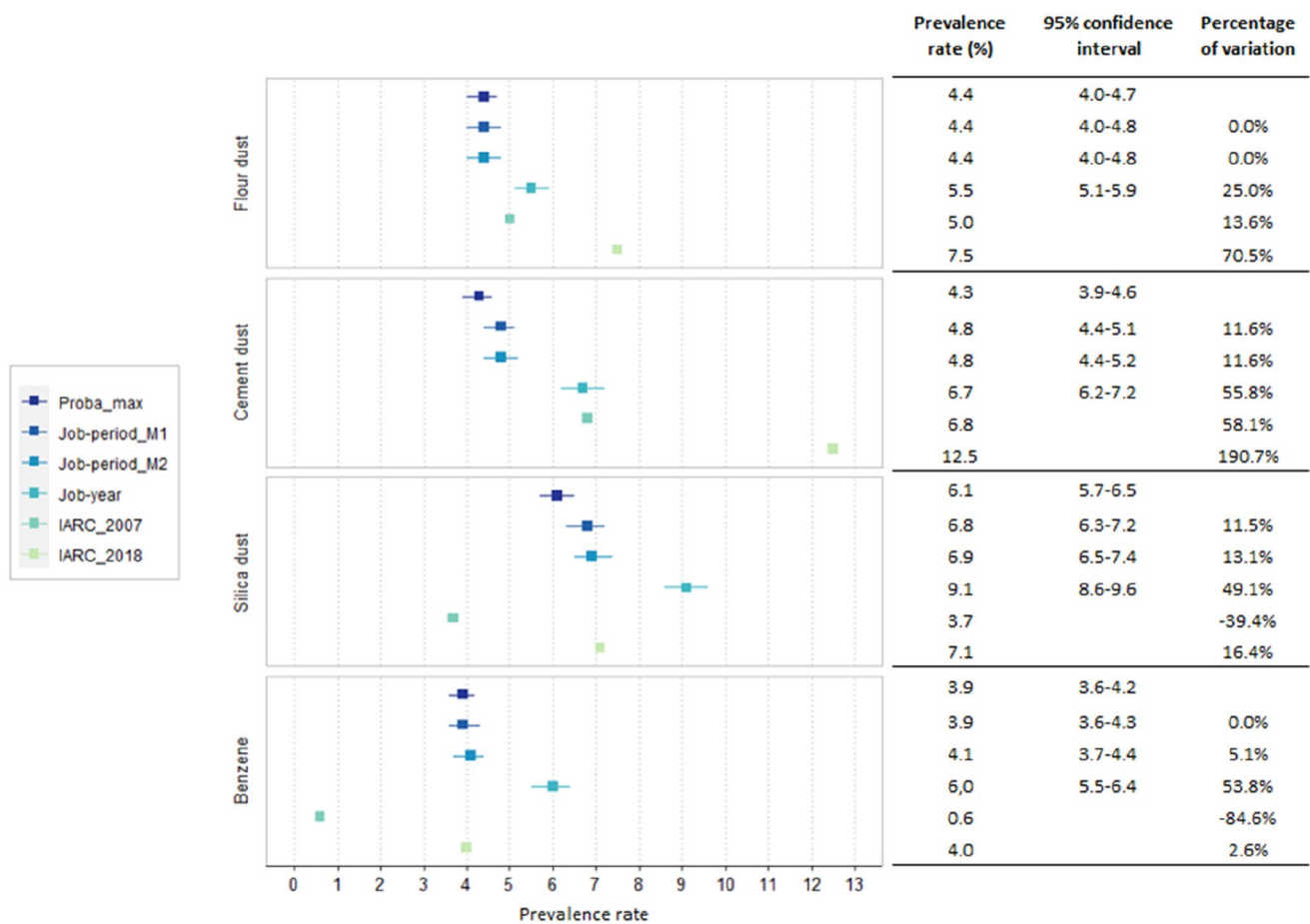
Fig. 2 Comparison of LOEP on the different methods for the entire study population.

95% CI 95% confidence interval; Percentage of variation between Method *n* and Proba_max, *Proba_max* maximum exposure probability during the career, *Job-period_M1* individual exposure probability based on subdividing the career into job-periods grouped on probability, *Job-period_M2* individual exposure probability based on subdividing the career into job-periods grouped on probability, intensity and frequency, *Job-year* individual exposure probability estimated by career cut into job-years, *IARC_2007* occupational exposure proportion from the 2003 SUMER study multiplied by a factor 3, *IARC_2018* occupational exposure proportion from the 2003 SUMER study multiplied by a specific age–gender factor

Results

LOEP was estimated for the entire population on the above methods and for four agents, as shown in Fig. 2.

When regarding the methods using full occupational histories, whichever the agent, proportion estimated from the maximum probability during the career (Proba_max) was consistently lower than proportion taking account of job-periods or job-years. LOEP using Proba_max for flour dust, cement dust, silica dust and benzene were, respectively, 4.4% 95% CI (4.0–4.7), 4.3% (3.9–4.6), 6.1% (5.7–6.5) and 3.9% (3.6–4.2).

Whichever the agent, the two methods taking account of job-periods (job-period_M1 and job-period_M2) all showed similar estimates, with a trend toward lower proportion with job-period_M1 (grouped only on exposure probability) and higher proportion with job-period_M2 (grouped on exposure

probability, intensity and frequency): for benzene, 3.9% 95% CI (3.6–4.3) with job-period_M1 and 4.1% (3.7–4.4) with job-period_M2 (Fig. 2).

Depending on the nuisance, variation between the job-period method grouped only on probability (job-period_M1) and the method using the maximum exposure probability throughout the career (Proba_max) ranged from 0% for flour dust and benzene to 11.6% for cement dust. Variation between the job-period method grouped on all exposure indices (job-period_M2) and Proba_max ranged from 0% for flour dust to 13.1% for silica dust.

The job-year method which breaks each job into one-year period (job-year), on the other hand, gave much higher estimates than the other methods: 25.0–55.8% higher than the method using the maximum exposure probability throughout the career (Proba_max), depending on the agent.

Table 3 Population-attributable fraction (PAF) estimates based on different LOEP estimation methods in 2017 in France

LOEP estimation method	Exposure to silica–lung cancer			Exposure to benzene–acute myeloid lymphoma		
	Silica LOEP	PAF (%)	N lung cancer[a] (N = 41,924)	Benzene LOEP[b]	PAF (%)	N AML[c] (N = 1452)
Proba_max	6.1 (5.7–6.5)	1.2 (0.6–1.8)	505 (254–753)	1.2 (1.0–1.4)	1.1 (0.5–3.5)	16 (7–51)
Job-period_M1	6.8 (6.3–7.2)	1.3 (0.7–2.0)	559 (282–833)	1.2 (1.0–1.4)	1.1 (0.5–3.6)	16 (7–52)
Job-period_M2	6.9 (6.5–7.4)	1.4 (0.7–2.0)	571 (288–851)	1.3 (1.1–1.5)	1.1 (0.5–3.6)	16 (7–53)
Job-year	9.1 (8.6–9.6)	1.8 (0.9–2.7)	749 (378–1114)	1.5 (1.3–1.7)	1.3 (0.6–4.3)	19 (9–62)
IARC_2007	3.7	0.7 (0.4–1.1)	306 (154–457)	0.3	0.3 (0.1–1.0)	4 (2–12)
IARC_2018	7.2	1.4 (0.7–2.1)	712 (360–1055)	0.6	0.5 (0.2–1.7)	6 (3–21)

[a]Number of incident cases of lung cancer in 2017 in France in the population aged 35–84 years old (population which is aged between 25 and 74 years in 2007)

[b]LOEP for benzene has been calculated for a short period of exposure (between 0 and 20 years)

[c]Number of incident acute myeloid leukemia in 2007 in France in the population aged 25–74 years old

When regarding the two IARC methods which uses cross-sectional occupational proportion multiplied by a factor, we can see that each method gave heterogeneous results for a same agent. The IARC_2007 method, using a factor 3, sometimes estimated lower proportions than the method using the maximum exposure probability throughout the career (Proba_max) as for benzene or silica dust (0.6% vs 3.9% and 3.7% vs 6.1%) and sometimes higher estimates such as for cement dust (6.8% vs 4.3%). On the other hand, the IARC_2018 method estimates, using an age–gender-specific factor, are always higher than Proba_max but with different variation levels, from 2.6 to 16.4% for benzene and silica dust and from 70.5 to 190.7% for flour and cement dust.

The population-attributable fraction based on the LOEP estimates from different methods are presented in Table 3. The PAF for exposure to silica and onset of lung cancer are very similar between the method using the maximum exposure probability throughout the career (Proba_max), the methods using the job-periods (job-period_M1, job-period_M2) and the method from IARC developed in 2018 with an age–gender-specific factor [PAF_{Proba_max} = 1.2% 95% CI (0.6–1.8), $PAF_{job-period\_M1}$ = 1.3% (0.7–2.0), $PAF_{job-period\_M2}$ = 1.4% (0.7–2.0) and PAF_{IARC_2018} = 1.4% (0.7–2.1), respectively]. The impact from those little variations was estimated as a fluctuation of about 200 lung cancer cases attributable to silica exposure between Proba_max and *IARC_2018*. On the other hand, the method developed by IARC in 2007 using a factor 3 gives a PAF reduced by 40% compared to the Proba_max method (N = − 199 lung cancer cases attributable to silica exposure). Conversely, the method which breaks each job into one-year period (job-year) gives a much higher PAF, 1.5

times higher than the PAF given by Proba_max (N = + 244 lung cancer cases). The same trend can be observed in PAF for exposure to benzene and onset of acute myeloid leukemia (AML) with very little variations between the three methods (Proba_max, job-period_M1, job-period_M2) with the same number of AML cases attributable to benzene exposure. The two IARC methods (IARC_2007 and IARC_2018) gave a PAF reduced by 70% and 55%, respectively, compared to Proba_max method (N = − 12 and − 10 AML cases) and job-year method estimated 19% more AML cases (+ 3 cases), compared to Proba_max.

Discussion

The lifetime occupational exposure proportion estimation methods presented in this article, when using full occupational histories, present a trend toward lower proportion using the maximum probability during the career (Proba_max) and higher proportion with the exposure assessment cut in job-year (job-year). The two methods using exposure cut in job-periods are included in this interval. The widest variations observed in job-period_M2 (job-periods with the same probability/intensity/frequency exposure) compared to Proba_max concerned mineral dust (cement and silica dust), for which scales were more detailed, with 10-category probability and frequency scales, compared to four categories for the other agents. For cement dust, exposure intensity was assessed on five categories, compared to four categories for the other agents. For job-year, on the other hand, the variation was greater for agents occurring

in multiple jobs even when there were only low exposure probabilities, such as cement or silica dust, or for nuisances for which the regulations had changed considerably over time, such as benzene. Conversely, agents specific to a given population of workers and strongly dichotomized according to the job (high versus low exposure probability), such as flour dust, showed less variation.

When using the cross-sectional occupational exposure proportion multiplied by a factor, we do not observe a similar trend as for method using full occupational histories, as the percentage variation can be positive or negative depending on the agent and the method used. Indeed, the 2007 IARC method has used a general factor for every agent and therefore has considered that each agent had a stable evolution which is clearly not the case for benzene which has majorly decreased after 1990 due to French regulations (Pilorget et al. 2007). The 2018 IARC method had tried to correct this problem using age–gender-specific factor depending on the evolution of the agent in time (prevalence stable, dropped moderately, dropped dramatically over time). Therefore, we can see that for benzene, this approach has worked but for agents where prevalence have dropped moderately, the factor is not specific enough and therefore some prevalence can be overestimated such as for cement or flour dust. Although, this method can be useful when no occupational histories are available, the method using cross-sectional occupational proportion to estimate LOEP needs to be improved using age–gender factor more specific of each agent. An IARC workgroup is in progress to develop an agent specific model taking into account more prevalence for a given year over the period studied when the only available data are cross-sectional proportion (Marant Micallef et al. 2020).

Analyses were based on a representative sample of the French population in 2007, with all of the jobs comprising their careers, regardless of occupational status (employees, self-employed workers, retired, not working, etc.). Such analysis could also be applied to any data comprising individual's occupational history. For example, the various LOEP calculations were implemented in a specific population of retired self-employed craftspeople in a post-occupational surveillance programme and a cohort study (ESPrI) (Goulard and Homere 2012; Goulard et al. 2015), and these results are presented in a supplement to the present article (Supplement II).

Analyses in the ESPrI cohort regarding silica dust showed the same LOEP trends as in the present study, with Proba_max giving the lowest proportion and job-year the highest. For job-period_M1 and job-period_M2, in contrast, variations were much greater in the ESPrI cohort, ranging from 22 to 24% for the entire population, compared to 11–13% in the general population. This may be due to greater exposure proportion than in the general population using Proba_max:

27.9% vs. 6.1%. Retired self-employed craftswomen had much lower exposure proportion on Proba_max (1.2%) and showed variations much closer to those found in the general population. Variations on job-year were comparable in both populations: 40.5% and 49.1%.

Proba_max uses a single assessment: maximum probability during the career; it is thus easy to use and does not require multiple probability assessments. However, it probably underestimates exposure proportion, as it does not take account of exposure over the entire career but only for one job: the most probably exposed job, even if it lasted 1 year. Estimation methods using job-periods (job-period_M1 and job-period_M2) or job-years (job-year) have the advantage of taking account of the entire job history and, thus, of all of the probabilities for each job. Job-year, gets round the problem of differences due to the number of periods defined in the matrices, and also indirectly takes account of exposure duration, as the number of job-years is the same as the number of years of exposure. However, the main limitations of these methods is its strong assumption of independence between jobs and the independence between job-periods or job-years and exposure. In reality, the jobs comprising a career are not independent of each other, and still less are the periods (annual or other) of exposure within a given job. However, the data necessary to manage these limitations are, to the best of our knowledge, not available.

In addition, the exposure in the IARC methods was based on an exposure survey filled by the occupational physician on the work week prior to the workers' interview compared to an exposure assessment over the entire career obtained by the JEMs.

The present study dealt with various methods of estimating LOEP, but not with all; other methods exist, such as taking account of the probability in the longest job. These methods are used mostly when complete job history is not available, which was not the case in the present study. Considering the various methods presented here, the precise LOEP estimates is difficult to achieve, and it is not always possible to choose between methods, due to limited data. However, it seems that LOEP when the occupational history is available is closer to the estimates provided by the various methods based on job-periods (i.e., job-period_M1 and job-period_M2), with the advantage of taking account of exposure in all jobs comprising the career. Indeed, a career is not often linear, and more often recently. Many changes can appear during the course of it, changes in jobs and professional paths which is not taken into account with the IARC methods. The consideration of the exposure over the entire career is also particularly important when studying sub-populations of workers such as the retired self-employed workers from the ESPrI cohort.

Few studies have focused on LOEP using full occupational career linked with job-exposure matrices, and

estimation methods are almost never detailed, making comparison difficult. These occupational proportions are important, and are often used to estimate other indicators such as the contribution of occupational exposure in a given disease. Depending on the method used, the number of cancer cases can vary from one to two in the case of the exposure to silica and onset of lung cancer and from one to four in the exposure to benzene and onset of acute myeloid lymphoma. For purposes of surveillance, intended to lead to prevention policies, it is important, therefore, to be vigilant to take into account all the parameters previously presented when publishing LOEP results: it is preferable to publish LOEP using exposure assessment over the entire career whether this exposure is assessed by job-exposure matrix or by expertise and LOEP should be reported as intervals, including low estimates using job-period_M1 and high estimates on job-period_M2. The use of one exposure proportion for a given year to estimate LOEP should be limited when the exposure is stable over the period considered or if precise data are available concerning the trend of exposure over the years.

Conclusion

The present study provides the first detailed description of several methods of calculation used to estimate lifetime occupational exposure proportion in the general population and their impact on population-attributable fraction estimates. It specifies the strong and weak points of each of the four chosen methods using the full occupational history, maximum probability of exposure during the career, probability from career breakdown in job-periods (two different methods) or job-years. It also compares those results with estimation methods using cross-sectional occupational proportion multiplied by a factor. These results are useful for research team in occupational exposure, in particular when using job-exposure matrices on their data to estimate the burden of disease of an occupational agent. It recalls that lifetime occupational exposure proportion estimation methods should preferably use LOEP based on exposure assessment on full occupational history compared to LOEP obtained using cross-sectional exposure proportion multiplied by a factor when it is possible, particularly on agents with major changes over the exposure period. For health monitoring purposes, LOEP is a major indicator in occupational health surveillance and public health, it should be reported as intervals, with low and high estimates obtained on different methods using job-periods to take account of the overall career, changes in exposure in the course of time and better estimate population-attributable fraction.

Declarations

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