Modelling of exposure to respirable and inhalable welding fumes at German workplaces

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ABSTRACT

The International Agency for Research on Cancer classified welding fume as carcinogenic to humans, and occupational exposure limits should be established to protect welders. The aim of this study is to estimate exposure levels to inhalable and respirable welding fumes by welding process to use them for exposure assessment in epidemiological studies and to derive occupational exposure limits. In total, 15,473 mass concentrations of inhalable and 9,161 concentrations of respirable welding fumes could be analyzed along with welding-related and sampling information, which were compiled in the German database MEGA between 1983 and 2016. In both particle-size fractions, model-based geometric means of the concentrations were estimated by welding process and material for frequently used welding processes adjusted for sampling time and median-centered for calendar years. The inhalable concentrations were approximately twice the respirable concentrations, with medians of 3 mg/m³ (inter-quartile range: 1.2–7.0 mg/m³) and 1.5 mg/m³ (inter-quartile range: < limit of detection – 3.8 mg/m³), respectively. The adjusted geometric means of flux-cored arc welding, metal inert and active gas welding, shielded metal arc welding and torch cutting ranged from 0.9 to 2.2 mg/m³ for respirable welding fumes and from 2.3 to 4.7 mg/m³ for inhalable fumes. In both particle-size fractions, geometric means were between 0.1 and 0.9 mg/m³ when performing tungsten inert gas, autogeneous, resistance, laser, and plasma welding or spraying. Results derived from this large dataset are useful for a quantitative exposure assessment to estimate health risks of welders.

KEYWORDS

Adjusted geometric means; MEGA exposure database; welders; welding-fume concentrations

Introduction

Welding is a primary industrial process, the performance of which exposes approximately 120 million workers who work either as welders or in trades that include welding as part of their job. The International Agency for Research on Cancer (IARC) classified welding fume as carcinogenic to humans. Since the first evaluation, mounting evidence of an increased lung cancer risk emerged from epidemiological studies. Data describing the increased lung cancer risk associated with welding is frequently based on job title or task. However, these broad descriptors often do not capture the wide variation in welding fume exposures that are due to the fundamental differences in the various welding processes employed. For example, welding fume concentrations were usually highest in flux-cored arc welding (FCAW), whereas concentrations determined during tungsten inert gas welding (TIG) were low.

Recently, 13 countries have a specific exposure limit for welding fumes ranging between 1 mg/m³ in the Netherlands to 4 or 5 mg/m³ in the other countries. However, the particle-size fraction was frequently not defined, as it is assumed that the welding fumes are respirable. Germany and the United States have not yet set a specific limit value for welding fumes.

Exposure databases compiling welding fume concentrations have been established in several countries. Here, we took advantage of a large collection of personal measurements of respirable and inhalable welding fumes from the German database MEGA...
“Messdaten zur Exposition gegenüber Gefahrstoffen am Arbeitsplatz” along with ancillary information on the sampling conditions, workplaces and welding processes. This database has been used to report on exposure levels at German workplaces and for the chemical safety assessment of REACH.

The objective of this study is to estimate exposure to respirable and inhalable welding fumes by welding process and material to support the exposure assessment of welders when estimating the lung cancer risk in community-based studies.

**Methods**

**Measurements of respirable and inhalable welding fumes**

Mass concentrations of welding fumes were gathered within the framework of the measurement system for hazard determination (MGU) of the German Social Accident Insurance (DGUV). These data were documented along with information on the sampling and welding process in the exposure database MEGA compiled at the Institute for Occupational Safety and Health of the DGUV.

This paper presents the results of the analysis of 15,473 personal measurements of inhaleable and 9,161 measurements of respirable welding fumes collected between 1983 and 2016.

Table 1 lists the various samplers used throughout this time period. All samplers were positioned on the welder without side preference and usually outside of the helmet. FSP samplers contained a cellulose nitrate filter with a pore size of 8 μm and a diameter of 37 mm. GSP samplers were usually equipped with 37-mm diameter glass-fiber filters. Both FSP and GSP samplers comply with international standards (EN 481, ISO 7708, EN 1286).

Since the 1990s, the samplers FSP 2 (2 L min⁻¹, n = 2,207) and FSP 10 (n = 4,417) were used to collect the respirable fraction. GSP 3.5 was the most frequently applied sampler (n = 11,159) to collect inhalable welding fumes. Two historical samplers operating at a flow rate of 2 L min⁻¹ were used to collect inhalable welding fumes prior to the definition of these standards. A foam selector of the more recently developed PGP-EA sampler allowed a separation of respirable and inhalable particles.

The particle-loaded filters were shipped to IFA for laboratory analyses. They were equilibrated to the laboratory atmosphere for at least 24 hr. Mass concentrations were determined gravimetrically by weighing with a method previously described in compliance with ISO 15767. The limit of detection (LOD) was three times the standard deviation of the weight difference before and after shipment for a minimum of 10 field-blank filters. The individual LOD depends on the particle mass collected on the filter, which is influenced by the airborne welding fume concentration and the duration of the measurement among other factors.

We took advantage of a categorical variable in MEGA, which was used by the metrologists to assign the welding or cutting of metals to commonly used processes. High fume emission processes include FCAW, metal active gas welding (MAG), metal inert gas welding (MIG), shielded metal arc welding.
(SMAW), and torch cutting. Furthermore, other welding processes include TIG, resistance welding, laser welding, submerged arc welding, plasma welding, autogenous welding, plasma cutting, flame spraying, plasma spraying, and arc spraying. Four consumable categories for dominant welding processes (MAG, MIG, TIG, SMAW) were defined. The three common consumables were mild steel, stainless steel, and aluminium (Al). The fourth category, labeled “other/mixed content” includes miscellaneous consumables or data for which the consumable was not identified. The metal content (%) was documented in MEGA for both the consumable and the base metal. We classified consumable electrodes as stainless steel if the chromium (Cr) or/and nickel (Ni) content exceeded 10%. Otherwise, ferrous consumables were classified as mild steel. The category “high Al” means a content of at least 95%. In the case of processes that did not use consumable electrodes, this classification was applied to the base material.

**Statistical analysis**

The distributions of the mass concentrations of inhalable and respirable welding fumes were described with the fraction of measurements below LOD and selected percentiles (P25, P50, P75, P90, P95) using the raw data from MEGA and stratified by welding process and other factors. P50 presents the median value, and the interval from P25 to P75 is the interquartile range (IQR), which contains 50% of the measurements.

The technique of multiple imputation, which utilizes the distribution of all measurements above the LOD, was used to incorporate measurements below the LOD. In brief, an interval where the lower bound was set to zero and the upper bound was set to the specified LOD were defined and postulated that the probability distribution of concentrations within this interval (0 to LOD) depends on all measurements above LOD and generated 10 data sets, each with a random set of imputed measurements. Furthermore, these data sets were analyzed with the same regression model. Subsequently, estimates of the regression coefficients $\beta_i$ from all 10 runs were combined.

To estimate the average level as geometric means (GMs) of exposure to welding fume by welding process and material for each particle-size fraction, we centered GMs at the median calendar year and presented GMs adjusted and not adjusted for the duration of sampling. Adjusted $R^2$ was estimated for goodness-of-fit of the respective regression model.

The fully adjusted model was defined as:

$$\ln (\text{Welding fume}) = \text{Intercept} + \beta_1 \times \text{Welding process} + \beta_2 \times \text{Material} + \beta_3 \times \text{Year} + \beta_4 \times \ln (\text{Duration}) + \epsilon.$$  

(1)

All calculations were performed with the statistical software SAS (version 9.4, SAS Institute Inc., Cary, NC).

**Results**

Figure 1 shows the distribution of all welding fume concentrations in both particle-size fractions with imputed data for measurements < LOD, collected from 1983 to 2016. Table 2 presents the distributions of welding fume concentrations with percentiles and stratified by various factors using raw data. Among 9,161 concentrations in the respirable fraction, 26% were below LOD, the median was 1.5 mg/m$^3$, the 75th percentile 3.8 mg/m$^3$, and the 95th percentile 14.1 mg/m$^3$. The corresponding parameters derived from 15,473 measurements of inhalable welding fumes were 3.0 mg/m$^3$, 7.0 mg/m$^3$, and 21.8 mg/m$^3$, and 23% of the measurements did not reach LOD. LODs could be reduced to median values of approximately 0.6 mg/m$^3$ until the 1990s (data not shown).
Table 2. Distribution of personal measurements of respirable and inhalable welding fumes (MEGA database, 1983–2016).

| Characteristics | Respirable fraction | Inhalable fraction |
|-----------------|---------------------|--------------------|
|                 | N | N < LOD % | P25 mg/m³ | P50 mg/m³ | P75 mg/m³ | P90 mg/m³ | P95 mg/m³ | N | N < LOD % | P25 mg/m³ | P50 mg/m³ | P75 mg/m³ | P90 mg/m³ | P95 mg/m³ |
| Total           | 9,161 | 26 | <LOD | 1.5 | 3.8 | 8.7 | 14.1 | 15,473 | 23 | 1.2 | 3.0 | 7.0 | 14.3 | 21.8 |
| Sampler         |                |                |                |                |                |                |                |                |                |                |                |                |                |                |
| FSP 2           | 2,207 | 29 | <LOD | 2.2 | 5.1 | 11.4 | 17.2 |          |          |          |          |          |          |          |
| FSP 10          | 4,417 | 21 | 0.4  | 1.2 | 3.2 | 8.3  | 13.8  |          |          |          |          |          |          |          |
| GSP-EA          | 2,537 | 33 | <LOD | 1.4 | 3.4 | 7.0  | 11.5  |          |          |          |          |          |          |          |
| Sampler with 30 mm filter holder |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Multihole sampler |          |          |          |          |          |          |          |          |          |          |          |          |          |
| GSP 3.5         | 11,159 | 21 | 0.9  | 2.6  | 6.6  | 13.9  | 21.2  |          |          |          |          |          |          |          |
| GSP-10          | 1,004 | 21 | 0.5  | 1.4  | 4.2  | 10.2  | 18.9  |          |          |          |          |          |          |          |
| PGP-EA 3.5      | 1,971 | 18 | 2.4  | 4.3  | 8.8  | 16.4  | 24.4  |          |          |          |          |          |          |          |
| Time of measurement [years] |          |          |          |          |          |          |          |          |          |          |          |          |          |
| 1983–<1997      | 603 | 24 | 1.2  | 2.0  | 5.0  | 12.0 | 20.0  |          |          |          |          |          |          |          |
| 1997–<2006      | 2,099 | 22 | 0.8  | 2.0  | 4.8  | 10.7 | 16.2  |          |          |          |          |          |          |          |
| 2006–<2011      | 2,871 | 27 | <LOD | 1.6 | 3.8 | 8.1  | 13.0  |          |          |          |          |          |          |          |
| 2011–2016       | 3,588 | 29 | <LOD | 1.2 | 3.0 | 7.1  | 12.2  |          |          |          |          |          |          |          |

| Sampling time [hr] | Respirable fraction | Inhalable fraction |
|--------------------|---------------------|--------------------|
|                    | N | N < LOD % | P25 mg/m³ | P50 mg/m³ | P75 mg/m³ | P90 mg/m³ | P95 mg/m³ | N | N < LOD % | P25 mg/m³ | P50 mg/m³ | P75 mg/m³ | P90 mg/m³ | P95 mg/m³ |
| <2                 | 2,338 | 15 | 1.9  | 4.0  | 8.6  | 17.7 | 28.8  |          |          |          |          |          |          |          |
| 2–<3               | 5,392 | 31 | <LOD | 1.2 | 2.4 | 5.2  | 8.2   |          |          |          |          |          |          |          |
| 3–<4               | 776  | 29 | <LOD | 1.2 | 3.5 | 8.5  | 13.6  |          |          |          |          |          |          |          |
| ≥4                 | 755  | 26 | <LOD | 1.2 | 3.1 | 6.7  | 9.7   |          |          |          |          |          |          |          |

LOD: limit of detection; P25: 25th percentile; P50: 50th percentile; P75: 75th percentile; P90: 90th percentile; P95: 95th percentile.
Table 3. Distribution of personal measurements of respirable and inhalable welding fumes by welding process and material (MEGA database, 1983–2016).

| Process                          | Material                  | N     | N < LOD% | P25 mg/m³ | P50 mg/m³ | P75 mg/m³ | P90 mg/m³ | P95 mg/m³ |
|---------------------------------|---------------------------|-------|----------|-----------|-----------|-----------|-----------|-----------|
| Metal active gas welding        | Stainless steel           | 4,854 | 14       | 1.1       | 2.2       | 4.8       | 9.8       | 15.3      |
|                                | Metal steel               | 3,384 | 12       | 1.1       | 2.3       | 4.8       | 10.2      | 16.1      |
|                                | Stainless steel           | 457   | 28       | < LOD     | 1.2       | 2.9       | 6.7       | 11.6      |
|                                | High aluminum content     | 23    | 4        | 2.4       | 4.9       | 10.5      | 14.3      | 30.3      |
|                                | Other/mixed content       | 990   | 15       | 1.1       | 2.4       | 5.4       | 10.3      | 15.8      |
| Metal inert gas welding         | Mild steel                | 543   | 16       | 1.1       | 2.6       | 6.1       | 13.1      | 22.5      |
|                                | Stainless steel           | 117   | 11       | 1.2       | 2.6       | 6.1       | 12.8      | 30.5      |
|                                | High aluminum content     | 159   | 12       | 0.9       | 2.5       | 6.4       | 13.3      | 19.5      |
|                                | Other/mixed content       | 136   | 21       | 1.3       | 2.7       | 5.9       | 11.7      | 19.1      |
| Tungsten inert gas welding      | Mild steel                | 921   | 66       | < LOD     | 0.8       | 1.3       | 1.9       | 1.9       |
|                                | Stainless steel           | 133   | 49       | < LOD     | 0.7       | 1.0       | 1.9       | 5.2       |
|                                | High aluminum content     | 560   | 73       | < LOD     | < LOD     | 0.7       | 1.1       | 1.3       |
|                                | Other/mixed content       | 175   | 60       | < LOD     | < LOD     | < LOD     | 1.2       | 1.7       | 3.8       |
| Shielded metal arc welding      | Mild steel                | 521   | 26       | < LOD     | < LOD     | 1.6       | 4.2       | 10.1      | 18.8      |
|                                | Stainless steel           | 205   | 26       | < LOD     | < LOD     | 1.9       | 4.9       | 11.8      | 21.2      |
|                                | High aluminum content     | 92    | 35       | < LOD     | < LOD     | 1.6       | 5.1       | 11.3      | 27.4      |
|                                | Other/mixed content       | 175   | 60       | < LOD     | < LOD     | < LOD     | 1.2       | 1.7       | 3.8       |
| Flux-cored arc welding          | Mild steel                | 45    | 67       | < LOD     | < LOD     | 0.8       | 3.3       | 11.2      | 81        |
|                                | Autogenous welding        | 32    | 41       | < LOD     | 0.7       | 1.2       | 2.0       | 4.3       |
|                                | Other tasks               | 290   | 33       | < LOD     | 1.3       | 2.7       | 7.1       | 12.3      |

LOD: limit of detection; P25: 25th percentile; P50: 50th percentile; P75: 75th percentile; P90: 90th percentile; P95: 95th percentile.
The median of the sampling duration was 2 hr. About 24.4% of concentrations in the respirable fraction and 16.5% in the inhalable fraction were collected with a sampling duration of less than 2 hr with median concentrations of 4.0 mg/m³ of respirable and 16.5% in the inhalable fraction were collected. About 24.4% of concentrations in the respirable fraction (median 2.6 mg/m³).

Table 2, different samplers were used in these periods, with FSP 10 most frequently used to collect the respirable fraction (median 1.2 mg/m³). Also, SAMW was associated with relatively high concentrations (respirable: 1.6 mg/m³; inhalable: 3.4 mg/m³).

For both particle-size fractions, use of consumable electrodes of low Cr/Ni content (mild steel) resulted in higher exposure levels than those with a higher content (stainless steel) when performing MAG or SAMW. Measurements were frequently below LOD in several other welding processes, and median values could not be calculated with raw data. The 75th percentiles of measurements of respirable welding fumes in tungsten inert gas welding (TIG), resistance, and plasma welding or plasma spraying were below 1 mg/m³.

Table 4 depicts effect estimates from the regression models as factors modifying the average exposure level, with MAG and mild steel as reference groups. We refer to the adjusted estimates (exp(\(b\)) ± 95% CI), if not otherwise stated. Welders applying FCAW showed higher concentrations than MAG (respirable: 1.48, 95% CI 1.21–1.81; inhalable: 1.42, 95% CI 1.23–1.65). MIG was associated with slightly more respirable but...
Table 5. Model-based estimates of the geometric means of occupational exposure to welding fumes predicted with and without adjustment for sampling time. (MEGA database, 1983–2016).

| Process Material                      | Respirable fraction, mg/m³ | Inhalable fraction, mg/m³ |
|----------------------------------------|-----------------------------|---------------------------|
|                                        | Model with adjustment for 2 hr sampling time | Model without adjustment for sampling time | Model with adjustment for 2 hr sampling time | Model without adjustment for sampling time |
|                                        | Geometric Mean | 95% CI               | Geometric Mean | 95% CI | Geometric Mean | 95% CI | Geometric Mean | 95% CI |
| Metal active gas welding                | 1.6             | 1.4–1.8              | 2.0             | 1.9–2.3 | 3.3             | 3.2–3.4 | 3.8             | 3.7–4.0 |
| Mild steel                             | 1.7             | 1.7–1.8              | 2.3             | 2.2–2.4 | 3.9             | 3.7–4.0 | 4.5             | 4.4–4.7 |
| Stainless steel                        | 1.0             | 1.0–1.1              | 1.4             | 1.3–1.5 | 2.3             | 2.2–2.5 | 2.7             | 2.6–2.9 |
| High aluminum content                  | 1.6             | 1.4–1.9              | 2.1             | 1.8–2.5 | 4.1             | 3.5–4.7 | 4.8             | 4.1–5.5 |
| Other/mixed content                    | 1.4             | 1.4–1.5              | 1.9             | 1.8–2.0 | 3.3             | 3.1–3.4 | 3.8             | 3.6–4.0 |
| Metal inert gas welding                | 1.8             | 1.6–2.0              | 2.3             | 2.1–2.6 | 3.0             | 2.8–3.2 | 3.5             | 3.2–3.7 |
| Mild steel                             | 2.0             | 1.8–2.3              | 2.7             | 2.4–3.0 | 3.5             | 3.3–3.8 | 4.5             | 4.4–4.7 |
| Stainless steel                        | 1.2             | 1.1–1.4              | 1.6             | 1.4–1.8 | 2.1             | 2.0–2.3 | 2.5             | 2.3–2.7 |
| High aluminum content                  | 1.9             | 1.6–2.2              | 2.5             | 2.1–2.9 | 3.0             | 2.8–3.2 | 4.3             | 3.8–4.9 |
| Other/mixed content                    | 1.7             | 1.5–1.9              | 2.3             | 2.0–2.5 | 3.5             | 3.3–3.8 | 3.4             | 3.2–3.7 |
| Tungsten inert gas welding             | 0.3             | 0.3–0.4              | 0.4             | 0.3–0.5 | 0.7             | 0.7–0.8 | 0.8             | 0.8–0.9 |
| Mild steel                             | 0.3             | 0.3–0.4              | 0.4             | 0.4–0.5 | 0.9             | 0.8–0.9 | 1.0             | 0.9–1.1 |
| Stainless steel                        | 0.2             | 0.2–0.2              | 0.3             | 0.2–0.3 | 0.5             | 0.5–0.6 | 0.6             | 0.6–0.6 |
| High aluminum content                  | 0.3             | 0.3–0.4              | 0.8             | 0.8–1.0 | 0.9             | 0.8–1.0 | 1.0             | 0.9–1.2 |
| Other/mixed content                    | 0.3             | 0.3–0.3              | 0.4             | 0.3–0.5 | 0.7             | 0.7–0.8 | 0.8             | 0.8–0.9 |
| Shielded metal arc welding             | 0.9             | 0.9–1.1              | 1.2             | 1.1–1.4 | 2.3             | 2.1–2.4 | 2.6             | 2.5–2.8 |
| Mild steel                             | 1.1             | 1.0–1.2              | 1.4             | 1.3–1.6 | 2.7             | 2.5–2.8 | 4.5             | 4.4–4.7 |
| Stainless steel                        | 0.7             | 0.6–0.7              | 0.9             | 0.8–1.0 | 1.6             | 1.5–1.7 | 1.9             | 1.7–2.0 |
| High aluminum content                  | 1.1             | 0.8–1.2              | 1.3             | 1.1–1.6 | 2.8             | 2.4–3.3 | 3.3             | 2.8–3.8 |
| Other/mixed content                    | 0.9             | 0.8–1.0              | 1.2             | 1.1–1.4 | 2.2             | 2.1–2.4 | 2.6             | 2.5–2.8 |
| Resistance welding                     | 0.2             | 0.2–0.2              | 0.3             | 0.2–0.3 | 0.5             | 0.4–0.5 | 0.5             | 0.5–0.6 |
| Laser welding                          | 0.2             | 0.1–0.2              | 0.2             | 0.2–0.3 | 0.3             | 0.2–0.3 | 0.3             | 0.3–0.4 |
| Flux-cored arc welding                 | 2.2             | 1.8–2.7              | 2.9             | 2.4–3.5 | 4.7             | 4.0–5.4 | 5.5             | 4.7–6.3 |
| Submerged arc welding                  | 0.6             | 0.5–0.8              | 0.8             | 0.6–1.1 | 1.9             | 1.5–2.4 | 2.2             | 1.7–2.8 |
| Plasma welding                         | 0.3             | 0.2–0.4              | 0.4             | 0.2–0.6 | 0.7             | 0.5–0.9 | 0.8             | 0.6–1.1 |
| Autogenous welding                     | 0.3             | 0.2–0.5              | 0.4             | 0.3–0.6 | 0.9             | 0.6–1.2 | 1.0             | 0.8–1.4 |
| Torch cutting                          | 0.9             | 0.9–1.0              | 1.2             | 1.1–1.4 | 2.8             | 2.6–3.1 | 3.3             | 3.1–3.6 |
| Plasma cutting                         | 0.4             | 0.4–0.5              | 0.6             | 0.5–0.6 | 1.3             | 1.2–1.4 | 1.5             | 1.4–1.7 |
| Flame spraying                         | 0.3             | 0.2–0.4              | 0.4             | 0.3–0.5 | 1.0             | 0.8–1.2 | 1.1             | 0.9–1.4 |
| Plasma spraying                        | 0.1             | 0.0–0.2              | 0.1             | 0.1–0.3 | 0.6             | 0.4–0.8 | 0.7             | 0.5–0.9 |
| Arc spraying                           | 0.3             | 0.1–0.5              | 0.3             | 0.2–0.5 | 1.6             | 0.9–2.9 | 1.9             | 1.0–3.4 |
| Other tasks                            | 0.6             | 0.5–0.7              | 0.8             | 0.7–0.9 | 1.7             | 1.6–1.9 | 2.0             | 1.8–2.2 |

Discussion

The classification of welding fume as carcinogenic to humans is a challenge for setting occupational exposure limits to prevent lung cancer in welders. The purpose of this analysis was, therefore, to provide average concentrations of welding fumes for different welding processes and materials to support the quantitative exposure assessment in epidemiological studies. The ratio of inhalable to respirable mass concentrations was about 2, with medians of 3 mg/m³ (IQR 1.2–7.0 mg/m³) in inhalable and 1.5 mg/m³ (IQR < LOD–3.8 mg/m³) in respirable welding fumes. This dataset is a subset of all data compiled in MEGA and does not include an identifier of side-by-side
measurements. Therefore, we can only provide a rough estimate of this ratio, comparing the averages in these particle-size fractions. An additional analysis of measurements of respirable and inhalable particulate matter has been performed with concentrations above LOD compiled in MEGA with data that are considered as suitable to estimate that ratio between respirable and inhalable concentrations (unpublished results). The median ratio of 1.98 was in good agreement with our estimate for welding fumes. There was indication of a nonlinear shape of this ratio across the concentration range. A more precise estimate of this ratio requires the sampling of both particle-size fractions in parallel, like in the WELDOX study.\textsuperscript{[10]} FCAW, MIG, MAG, SMAW, and torch cutting had GMs from 0.9 to 2.2 mg/m\textsuperscript{3} for respirable and GMs from 2.3 to 4.7 mg/m\textsuperscript{3} for inhalable welding fumes. GMs were between 0.1 and 0.9 mg/m\textsuperscript{3} when TIG, autogeneous, resistance, laser and plasma welding or spraying in both particle-size fractions.

Strengths of this statistical analysis are the large number of 9,161 personal measurements in the respirable fraction and of 15,473 measurements in the inhalable fraction, along with ancillary data about the measurements and welding processes. A limitation is the use of different samplers in this period of more than 3 decades following technological progress and changes made to conventions. The assessment of cumulative exposure to welding fumes is an important step in estimating the lung cancer risk of welders. Notably, the concentrations in the respirable fraction are more appropriate than other particle-size fractions for an association with the lung cancer risk. Welding 40 years at the median of all measurements would result in a cumulative exposure of 60 mg/m\textsuperscript{3} x years in the respirable fraction and 120 mg/m\textsuperscript{3} x years in the inhalable fraction. A Finnish study used cut-offs of 100 and 200 mg/m\textsuperscript{3} x years for estimating the lung cancer risk in welders, where 10% and 2% of cases, respectively, were exposed in these categories.\textsuperscript{[5]}

The job title “welder” is associated with a wide range of exposure to welding fumes. A supplementary questionnaire was applied in various community-based studies to document welding process and materials.\textsuperscript{[4,9,30,31]} Cumulative exposure to welding fume can be calculated by linkage of this individual information on welding histories with exposure levels. The GMs from this analysis along with estimates for Cr(VI) and Ni\textsuperscript{16,17} can be used to update a welding process exposure matrix (WEM), which was developed for a cohort of European welders.\textsuperscript{[32]} Here, the estimates for major processes were lower than previously shown in this WEM, for example 4 mg/m\textsuperscript{3} instead of 6 mg/m\textsuperscript{3} for welding mild steel with MAG or MIG. The estimates of the WEM and published results showing lower concentrations when applying MAG, MIG, or SMAW to stainless steel as compared to mild steel and higher concentrations when welding aluminum. TIG welding is usually associated with lower mass concentrations, with average values between 0.3 and 1.1 mg/m\textsuperscript{3} depending on the particle-size fraction.\textsuperscript{[10,13,33]} FCAW had the highest exposure levels, with mean concentrations between 2 and 15 mg/m\textsuperscript{3}.\textsuperscript{[10,13,33–35]} MIG/MAG was associated with average concentrations between 1 and 4 mg/m\textsuperscript{3}, again depending on the particle-size fraction and other factors.\textsuperscript{[10,13,33,36]}

Several reasons may explain the lower exposure levels of these estimates from large datasets of measurements compared with the averages of the WEM of the European cohort of welders, which were mainly derived from published measurements.\textsuperscript{[32]} Historical literature usually reported arithmetic means, which are higher than GMs and do not represent the average of skewed data distributions. For MAG, we estimated 3.3 mg/m\textsuperscript{3} as adjusted GM in the inhalable fraction whereas the corresponding arithmetic mean was 7.1 mg/m\textsuperscript{3}. Furthermore, values < LOD were imputed according to the distribution of measurable concentrations, whereas the substitution of such measurements with a fixed value results in a biased estimated of the average concentration.

Besides differences in the statistical methods, a general reduction of exposure levels across calendar time may explain at least partially such a difference between the WEM of the historical cohort of welders and this analysis, for example due improved exhaust ventilation. Between 1983 and 2016, a relative decrease of measurements in high fume emission settings were observed, whereas, new technologies such as laser welding were growingly monitored with low exposure levels. When controlling for welding process and materials, the statistical modeling yielded a linear negative trend of 4% per year for respirable and of 3% for inhalable welding fumes in this period.

Various uncertainties can be introduced when collecting particles with different samplers.\textsuperscript{[37,38]} For example, side-by-side measurements of welding fumes revealed a factor of 1.6 between PGP-EA and GSP 10 for the inhalable fraction in a field study.\textsuperscript{[10]} We refrained from implementing the samplers into the model because of their tight correlation with calendar years. Historical devices were developed to comply with former norms, such FSP 2 with the BMRC.
Conclusions

A large dataset of measurements allowed the exploration of the distribution of welding fume concentrations at German workplaces. Overall, the concentrations in the inhalable fraction were about twofold higher as compared with respirable welding fumes. The GMs are useful for the calculation of cumulative exposure to welding fumes to estimate the lung cancer risk of welders. The present study showed large differences between welding processes. The job title “welder” is not specific enough, and supplemental information on welding processes and materials should be documented when calculating exposure to welding fumes in epidemiological studies.

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References

[1] Guha, N., Loomis, D., Guyton, K.Z., et al.: Carcinogenicity of welding, molybdenum trioxide, and indium tin oxide. Lancet Oncol. 18:581–582 (2017).
[2] IARC: Welding, indium tin oxide, molybdenum tri-oxide [Volume 118]. Lyon, France: IARC Monogr. Eval. Carcinog. Risks Hum., 2017.
[3] IARC: Chromium, nickel and welding [Volume 49]. Lyon, France: IARC Monogr. Eval. Carcinog. Risks Hum.; 1990.
[4] Matrat, M., Guida, F., Mattei, F., et al.: Welding, a risk factor of lung cancer: The ICARE study. Occup. Environ. Med. 73:254–261 (2016).
[5] Siew, S.S., Kauppinen, T., Kyyronen, P., Heikila, P., and E. Pukkala: Exposure to iron and welding fumes and the risk of lung cancer. Scand. J. Work. Environ. Health. 34:444–450 (2008).
[6] Sorensen, A.R., Thulstrup, A.M., Hansen, J., et al.: Risk of lung cancer according to mild steel and stainless steel welding. Scand. J. Work. Environ. Health. 33:379–386 (2007).
[7] Kendzia, B., Behrens, T., Jöckel, K.H., et al.: Welding and lung cancer in a pooled analysis of case-control studies. Am. J. Epidemiol. 178:1513–1525 (2013).
[8] Ambroise, D., Wild, P., and J.J. Moulin: Update of a meta-analysis on lung cancer and welding. Scand. J. Work. Environ. Health. 32:22–31 (2006).
[9] ’t Mannetje, A., Brennan P., Zaridze D., et al.: Welding and lung cancer in Central and Eastern Europe and the United Kingdom. Am. J. Epidemiol. 175:706–714 (2012).
[10] Lehnert, M., Pesch, B., Lotz, A., et al.: Exposure to inhalable, respirable, and ultrafine particles in welding fume. Ann. Occup. Hyg. 56:557–567 (2012).
[11] Spear, J.E: Welding fume and gas exposure. Welding fume exposure tends to be highly variable due to several exposure factors. Occup. Health. Saf. 80:64–65 (2011).
[12] Liu, S., Hammond, S.K. and S.M. Rappaport: Statistical modeling to determine sources of
variability in exposures to welding fumes. *Ann. Occup. Hyg.* 55:305–318 (2011).

[13] Flynn, M.R., and P. Susi: Manganese, iron, and total particulate exposures to welders. *J Occup. Environ. Hyg.* 7:115–126 (2010).

[14] Stamm, R.: MEGA-database: One million data since 1972. *Appl. Occup. Environ. Hyg.* 16:159–163 (2001).

[15] Gabriel, S., Koppisch, D., and D. Range: The MGU - A monitoring system for the collection and documentation of valid workplace exposure data. *Gefahrstoffe-Reinhalt. Luft.* 70:43–49 (2010).

[16] Pesch, B., Kendzia, B., Hauptmann, K. et al.: Airborne exposure to inhalable hexavalent chromium in welders and other occupations: Estimates from the German MEGA database. *Int. J. Hyg. Environ. Health.* 5:500–506 (2015).

[17] Kendzia, B., Pesch, B., Koppisch, D. et al.: Modelling of occupational exposure to inhalable nickel compounds. *J. Expo. Sci. Environ. Epidemiol.* 27:427–433 (2017).

[18] Kendzia, B., Van Gelder, R., Schwank, T. et al.: Occupational exposure to inhalable manganese at German workplaces. *Ann. Work. Expo. Health.* 61:1108–1117 (2017).

[19] European Committee for Standardization (CEN): Workplace atmospheres - Size fraction definitions for measurement of airborne particles: European Standard EN 481. London, UK: British Standards Institute, 1993.

[20] International Organization for Standardization: ISO 7708: Air quality - Particle size fraction definitions for health-related sampling, 1995.

[21] Kenny, L.C., Stancliffe, J.D., Crook, B. et al.: The adaptation of existing personal inhalable aerosol samplers for bioaerosol sampling. *Am Ind Hyg Assoc J.* 59:831–841 (1998).

[22] Lee, T., Kim, S.W., Chisholm, W.P., Slaven, J. and M. Harper: Performance of high flow rate samplers for respirable particle collection. *Ann Occup Hyg.* 54:697–709 (2010).

[23] Möhlmann, C.: "Simultane personenbezogene Probenahme der E- und A-Fraktionen in Schweißbräuchen." 2006. Available at http://www.ifa-arbeitsmapppedigital.de/IFA-AM_3025 (accessed November 13, 2018).

[24] Hahn, J.U.: "Aufarbeitsverfahren zur Analytik metallhaltiger Stäube: Institute for Occupational Safety and Health of the German Social Accident Insurance (IFA)." Available at https://www.ifa-arbeitsmapppedigital.de/download/pdf/006015.pdf. (accessed June 21, 2018).

[25] Hebisch, R., Fricke, H.H., Hahn, J.U., Lahaniatis, M., Maschmeier, C.P., and M. Mattenklott: Sampling and determining aerosols and their chemical compounds. Weinheim: The MAK Collection for Occupational Health and Safety, Part III. Air Monitoring Methods. Wiley-VCH, 2005.

[26] International Organization for Standardization: ISO 15767: "Workplace atmospheres - Controlling and characterizing uncertainty in weighing collected aerosols." Available at https://www.iso.org/obp/ui/#iso:std:iso:15767:ed-2:v1:en. (accessed June 21, 2018).

[27] Lotz, A., Kendzia, B., Gawrych, K., Lehnerdt, M., Brüning, T., and B. Pesch: Statistical methods for the analysis of left-censored variables. *GMS. Med. Inform. Biom. Epidemiol.* 9 (2013).

[28] Little, R., Rubin, D.B.: *Statistical analysis with missing data.* New York, NY: Wiley, 1987.

[29] Harel, O.: The estimation of \( R^2 \) and adjusted \( R^2 \) in incomplete data sets using multiple imputation. *J. App. Stat.* 36:1109–1118 (2009).

[30] Jöckel, K.H., Ahrens, W., Pohlabeled, H., Bolm-Audorff, U., and K. M. Muller: Lung cancer risk and welding: Results from a case-control study in Germany. *Am. J. Ind. Med.* 33:313–320 (1998).

[31] Vallieres, E., Pintos, J., Lavoie, J., Parent, M.E., Rachet, B., and J Siemiatycki: Exposure to welding fumes increases lung cancer risk among light smokers but not among heavy smokers: Evidence from two case-control studies in Montreal. *Cancer. Med.* 1:47–58. (2012).

[32] Gerin, M., Fletcher, A.C., Gray, C., Winkelmann, R., Boffetta, P., and L. Simonato: Development and use of a welding process exposure matrix in a historical prospective study of lung cancer risk in European welders. *Int. J. Epidemiol.* 22:22–28 (1993).

[33] Hobson, A., Seixas, N., Sterling, D., and B. A. Racette: Estimation of particulate mass and manganese exposure levels among welders. *Ann. Occup. Hyg.* 55:113–25 (2011).

[34] Kiefer, M., Trout, D., and M. E. Wallace: *Health Hazard Evaluation Avondale Shipyards, Avondale Louisiana.* National Institute for Occupational Safety and Health; HHE Report 97-0260-2716:8 (11–98).

[35] Wallace, M., Shulman, S., and J. Sheehy: Comparing exposure levels by type of welding operation and evaluating the effectiveness of fume extraction guns. *Appl. Occup. Environ. Hyg.* 16:771–779 (2001).

[36] Pesch, B., Lehnerdt, M., Weiss, T. et al.: Exposure to hexavalent chromium in welders: Results of the WELDOX II field study. *Ann. Work. Expo. Health.* 59(1 Pt 2):467 (2018).

[37] de Vocht, F., Straif, K., Szeszenia-Dabrowska, N. et al.: A database of exposures in the rubber manufacturing industry: Design and quality control. *Ann. Occup. Hyg.* 49:691–701 (2005).

[38] Kenny, L. C., Aitken, R., Chalmers, C. et al.: A collaborative European study of personal inhalable aerosol sampler performance. *Ann. Occup. Hyg.* 41:135–153 (1997).

[39] Orenstein A.J.: "Recommendations adopted by the pneumoconiosis conference." *Proc. Pneumoconiosis Conference,* Johannesburg, 1959. London, UK: J & A Churchill, 1960.

[40] Görner, P., Wrobel, R., Fabries, J. F. et al.: Measurement of sampling efficiency of porous foam aerosol sampler prototypes. *J. Aerosol Sci.* 32: 1063–1064 (2001).