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A meta-analysis of airborne asbestos fiber concentrations from work with or around asbestos-containing floor tile

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ABSTRACT

In this meta-analysis, exposures to airborne asbestos during work with or around floor tiles were characterized according to several variables: study, sample type, activity, and task. Personal breathing zone, bystander, and area sample exposure concentrations were differentiated and compared against current occupational exposure limits to asbestos. In total, 22 studies, including 804 personal, 57 bystander, and 295 area samples, were included in the analysis. The arithmetic mean airborne fiber concentrations were 0.05, 0.02, and 0.01 f/cm^3 for personal, bystander, and area samples, respectively. Arithmetic mean time-weighted-average fiber concentrations over an 8-h working day were 0.02 and 0.01 f/cm^3 for personal and bystander samples, respectively. Phase contrast microscopy (PCM) personal airborne fiber concentrations were highest for maintenance activities, followed by removal and installation. Tasks that involved buffing or burnishing, scoring or snapping, and scraping or lifting had the highest personal PCM concentrations, while stripping floor tile and removing it with chemical solvent had the lowest concentrations. Exposures associated with handling asbestos floor tiles, under working conditions normally encountered, do not generally produce airborne concentrations at levels that exceed the current OSHA PEL nor do they appear to approach the threshold cumulative asbestos dose concentrations that have been previously associated with an increased risk of asbestos-related disease.

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Introduction

Asbestos-containing floor tiles were among the most common building materials between 1930 and 1980 [1]. The floor tile industry historically produced two main types of products: vinyl-asbestos tile (VAT) and asphalt-asbestos tile. VAT production accounted for up to 95% of the asbestos used by the floor tile industry [2]. Historically, the widespread and increasing use of asbestos floor tiles, and VAT in particular, was a result of the cost-effectiveness in covering large amounts of surface area. Furthermore, VAT is resistant to physical and chemical degradation and is often used in areas of high traffic or with potentials for spills of liquid or solid materials (e.g. kitchens, cafeterias, or washrooms) [3,4]. In the 1980s, manufacture and use of asbestos-containing floor tiles began to decrease. For example, in 1981, the production of VAT was 58,352,864 square yards, but by 1985, production had decreased to 18,300,000 square yards [3]. VAT production eventually ceased by the end of 1986 [3]. Although there is little evidence as to why the six primary processors of asbestos vinyl tile opted to phase out asbestos from their products, presumably this action was in response to the passage of the Asbestos Hazard Emergency Response Act (AHERA) in 1986 or the Occupational Safety and Health Administration (OSHA) issuance of an emergency temporary standard for the permissible exposure limit (PEL) of asbestos from 2 to 0.5 f/cm^3 [5]. Nonetheless, many current structures still contain asbestos-containing floor tiles. The United States Environmental Protection Agency (EPA) estimated that, in 1988, 42% of existing public and commercial buildings contained asbestos floor tiles [6].

Variability and changes in reporting requirements by state and within state districts make it difficult to determine the approximate number of public and commercial buildings that still contain asbestos-containing material (ACM). Many states do not maintain summary records of the total number of renovation and/or demolition permits received or the notifications specific to the National Emissions Standards for Hazardous Air Pollutants (NESHAP). In contrast, starting in 2015, Colorado published asbestos reports of permits and notifications issued by location, found at https://www.colorado.gov/pacific/cdphe/asbestos-reports-permits-and-notices-issued. According to the 2015, 2016, and 2017 data from Colorado, 6,471, 5,855, and 5,009 permits were issued, respectively, accounting for 4,835, 4,539, and 6,376 individual dwellings or units and 13,578,330, 12,824,726, and

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Supplemental data can be accessed here.

12,027,159 sq ft of ACM, as defined as containing greater than 1% asbestos content by weight. Of note, many locations did not report square footage in 2015. While not directly comparable to the EPA 1988 data for VAT in public and commercial buildings since the Colorado data include all ACM and not just VAT, these data indicate that a large number of sites with reported ACM are present in Colorado; an in-depth analysis of additional years' data from Colorado or from other states would be a beneficial addition to the asbestos literature.

Although formulations varied by manufacturer, VAT generally contained 5–30% by weight of asbestos, 15–25% binders or resins, with the remaining composition including other fillers, such as pigments, limestone, or plasticizers [2,7]. The fiber type generally used in VAT was chrysotile such that the fibers were distributed throughout the thickness of the tile [2,7,8]. There is no evidence to suggest that amphiboles ever constituted an ingredient of any VAT formulation, and this is consistent with the fact that many bulk-sampling analyses of VAT products have reported measurable levels of chrysotile but not amphibole [9–17]. Some studies have reported the presence of trace levels of amphibole. For example, in VATs from 28 different buildings evaluated by Kominsky et al. [8], the asbestos content ranged from 1% to 30%. The authors noted that over 99% of the asbestos content was chrysotile, while less than 1% was reported to be amphibole, as analyzed by transmission electron microscopy (TEM) [8]. However, it was not explained whether or not the amphibole was asbestiform nor did the authors speculate from where the amphibole may have originated. Another study conducted in an unoccupied building at a decommissioned air force base found that 99.6% of asbestos structures in VAT were chrysotile, while 0.4% of asbestos fibers were amphibole, as analyzed by polarized light microscopy (PLM). The presence of these amphibole fibers, however, was attributed to nearby fireproofing material that contained 60% crocidolite and 5% amosite asbestos [1]. Materials Analytical Sciences (MAS) [18] conducted PLM analysis of Flintkote Flexachrome VATs and reported that the tiles were composed of trace amounts chrysotile and non-asbestiform tremolite and/or actinolite. However, subsequent analysis of these same tiles (by MAS) using the Chatfield TEM method indicated the presence of 1.3–6.8% chrysotile and 2.2–4.1% tremolite [18]. It should be noted that indirect methods, such as the Chatfield method, have been shown to overestimate values [59].

Analyses of flooring mastics have also reported that chrysotile was the predominant or only fiber type detected. For example, Lange [19] evaluated various school buildings and noted that both VAT and mastic materials were between 2% and 7% chrysotile asbestos. A US Army Corps of Engineers study also noted that the mastic in various commercial buildings contained up to 20% asbestos, although fiber type was not specified [20]. Furthermore, in a simulation study conducted by Oberta and Fischer [10], the authors reported up to 50% chrysotile asbestos in mastic, with no detectable amphibole. To our knowledge, there have been no reports of any asbestiform amphibole fibers found in bulk or air concentrations in VAT or mastic materials that were not attributable to contamination from surrounding amphibole-containing materials.

With respect to the asbestos component, chrysotile, grades 5 and 7, was used in the production of VAT and asphaltic tiles due to affordability, use as binders, and to obtain the desired properties for strength, dimensional stability, and resistance to cold [2,9]. It has been noted that the majority (>90%) of structures in Grade 7 chrysotile are short and less than 5 μm in length [21]. The dry ingredients were combined in a Banbury mixer and distributed throughout the vinyl mass with liquids, and then heated, shaped, and cooled. Subsequently, the tiles were waxed, cut to size, inspected, and packaged [2,7]. The most common form of VAT is 9-by-9-in or 12-by-12-in squares [10,22]. Asphalt-asbestos floor tiles were manufactured in a similar manner and reportedly contained up to 40% asbestos [23]. VAT was also produced as sheets, similar to linoleum [9]. Unlike the individual tiles, the walk surface of sheet vinyl flooring did not contain asbestos, but the felt or paper backing (used to adhere the sheet to the flooring surface) contained approximately 40–75% short fiber chrysotile asbestos [9,24]. In addition to the resilient floor covering itself, the mastics used to adhere the floor covering have been reported to contain asbestos [10,11,20].

Asbestos-containing floor tiles are non-friable (cannot be crumbled or pulverized by hand-pressure alone) and the asbestos fibers are considered to be "encapsulated" in the tile or backing matrix [25]. The US OSHA acknowledged the limited potential for releasing fibers from encapsulated materials in 1972, when OSHA exempted encapsulated products from asbestos-labeling requirements if product use did not result in an exceedance of the contemporaneous OSHA PEL for asbestos of 5 f/cm^3, 8-h TWA[26]. The OSHA labeling exemption for encapsulated products remains in effect today [27]. The EPA also drew a distinction between friable and non-friable asbestos products in the early 1970s [28].

Resilient floor coverings can become damaged over time through wear and during certain handling and/or manipulation activities, such as removal and cleanup (scrape and lift, sweeping), installation (cutting, scoring, snapping, punching, drilling), and routine maintenance (buffing, burnishing) [2,8,10].

Asbestos-containing flooring is only considered friable if it is in poor condition, damaged, or "subjected to sanding, grinding, cutting or abrading" [29,30]. Recommendations for installing and removing resilient floor coverings, including VAT and asphalt-asbestos floor tile, have been published to help protect individuals who have the potential to be exposed to airborne asbestos generated from such aforementioned activities [31,32]. Specific to removal practices, recommendations to "never sand existing resilient floor covering," and warnings to avoid creating dust have been published [31]. Furthermore, all scraping and sweeping procedures "must be done wet" [32]. Assuming individuals adhered to such guidelines, the potential for airborne asbestos exposures would be expected to be below contemporaneous occupational exposure limits.

Hundreds of short-term (considered in this study to be generally less than 60 min) and time-weighted-average (8 h TWA) personal and area airborne asbestos concentrations measured during handling and use of asbestos-containing floor tiles at commercial and industrial sites [2,12,20,30,33–35], in schools [1,8,9,11,13–16,19,36–44], in residential settings [34,35,45], and in a simulated exposure environment [10,18,46–48] have been reported in over 30 published and unpublished studies. In general, most of the studies reported measurable asbestos levels with a large degree of heterogeneity. Although most samples, particularly those in the earlier years, were collected in the absence of any dust control measures, some studies evaluated effects of wet or dry methods, while others used techniques that allowed for distinguishing between asbestos and non-asbestos fibers via TEM analysis. The EPA reported that the estimated TWA of total fiber concentrations during machine buffing activities in the breathing zone of workers did not exceed the current OSHA PEL of 0.1-f/cm^3, 8-h TWA [49]. In contrast, Kominsky et al. [15] stated that all of the ultrahigh-speed (UHS) burnishing samples exceeded the current OSHA PEL, 8-h TWA. However, to the best of our knowledge, a thorough quantitative analysis of the combined body of these data, including the potential exposures and health risks associated with various tile-handling activities, has not been published. In particular, a comparison of the potential airborne fiber concentrations associated with work with or around asbestos floor tiles to the contemporaneous OSHA PELs that have changed over time has not been conducted. Thus, the purpose of this analysis was to evaluate airborne asbestos concentrations generated during various floor tile-handling activities and to characterize the potential exposures and health risks for a worker or bystander. In this analysis, we (1) conduct a statistical meta-analysis of published and unpublished airborne asbestos concentrations measured during work with or around floor tiles, by activity and by task; (2) compare tile-related airborne asbestos measurements to the OSHA 8-h TWA PEL over time; (3) characterize cumulative exposures to airborne asbestos for workers and bystanders; (4) compare floor tile-related cumulative asbestos exposures to published "no effect" exposure benchmarks for asbestos-related disease; and (5) identify data gaps and additional areas of research.

Methods

A comprehensive data search was conducted using several scientific databases, including PubMed, Web of Science, and Google Scholar. The search was not limited to the peer-reviewed scientific literature, as there were a number of other types of reports and surveys (e.g. industry and governmental industrial hygiene investigations and exposure simulation studies) that were publicly available. Studies conducted in residential, commercial, and industrial settings were included in the search. Peer-reviewed literature and unpublished documents were evaluated for airborne asbestos concentrations reported during the maintenance, removal, installation, routine clean-up, wear or trafficking, and abatement of asbestos-containing floor tiles via a title and abstract screen. Studies that passed the initial screen were evaluated for use in the meta-analysis (Figure 1).

Data censoring

Individual data points and summary exposure data were extracted from each publication, report, or survey. Censored data, or those samples reported as less than the limit of detection (LOD), were included in the statistical analysis using the regression on order statistics (ROS) method [50,51]. This method of linear regression fits the detected values of the data set to quantiles of the assumed distribution and replaces samples with values below the LOD with values extrapolated from the linear regression. ROS is a robust method recommended for data sets with variable LOD and is used in lieu of substitution methods (e.g. one-half the LOD). Excluded studies were those in which a sampling duration was not reported, where samples were identified as below the LOD and no LOD was provided, or those that acknowledged proximity to alternate asbestos exposure (e.g. simultaneous insulation sampling). There were no further criteria set for sampling duration with the exception of inclusion of a duration, but further discussion of short-term and long-term samples is included in the supporting information. A list of all studies included in the analysis is shown in Table 1. A

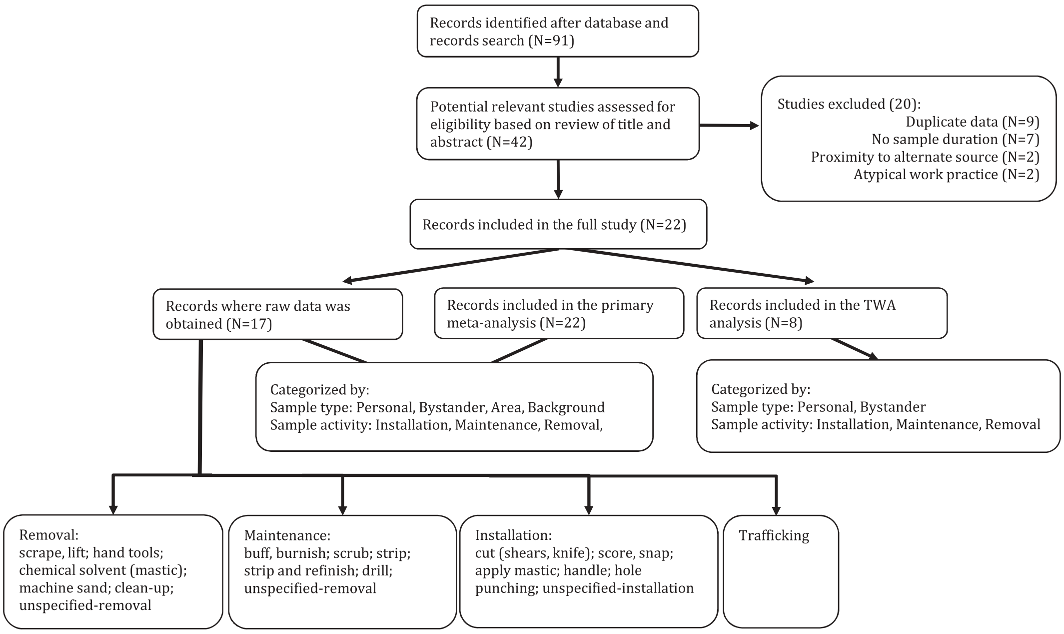

Figure 1. Overview of combined data set and description of data classifications.

Table 1. Studies containing airborne fiber concentrations resulting from work with or around asbestos-containing floor tiles included in the combined data set.

		Analysis		
No.	Reference	Reference type	Method (*N*)	Worker group(s)
1	Demyanek et al. [12]	Peer-reviewed	TEM (22)	Personal, area, baseline
2	Environ Corp. [35]	Report	PCM (41)	Personal, bystander
			TEM (25)	
3	Environ Corp. [33]	Report	PCM (8)	Personal
4	EPI [56]	Report	PCM (36)	Personal, bystander, area, baseline
			TEM (18)	
5	Ewing et al. [17]	Report	TEM (30)	Personal, area
6	Kominsky et al. [8]	Report	PCM (23)	Personal, baseline
			TEM (175)	
7	Kominsky et al. [1]	Peer-reviewed	PCM (15)**	Personal
8	Kominsky et al. [15]	Peer-reviewed	PCM (25)	Personal
			TEM (12)*	
9	Lange and Thomulka [11]	Peer-reviewed	PCM (25)	Personal, area
10	Lange and Thomulka [40]	Peer-reviewed	PCM (23)	TWA samples only
11	Lange [19]	Peer-reviewed	PCM (11)*	Personal
12	Lange [14]	Peer-reviewed	PCM (30)*	Personal
13	Lange [39]	Peer-reviewed	PCM (4)**	Personal
14	Lange et al. [37]	Peer-reviewed	PCM (25)	Personal
15	Lange et al. [38]	Peer-reviewed	PCM (35)	TWA samples only
16	Lundgren et al. [42]	Peer-reviewed	PCM (22)	Personal, area, baseline
17	Lundgren et al. [16]	Peer-reviewed	PCM (10)	Area
18	MAS [18]	Report	PCM (12)	Personal, area, baseline
			TEM (12)	
19	Oberta and Fischer [10]	Report	PCM (172)*	Personal, area
			TEM (20)	
20	Racine [43]	Peer-reviewed	PCM (238)**	Personal, area
21	USACE [20]	Report	PCM (114)	Personal, area
			TEM (34)	
22	Walcott and Warrick [45]	Report	PCM (5)	Personal, baseline

*Includes individual and summary data; ** Includes only summary data.

full list of all studies evaluated is shown in the supporting information in Table S1.

Data classification and statistical analysis

An initial assessment was conducted to evaluate factors across all studies, comprising both raw and summary data. The factors included sample type (personal, bystander, area), sample activity (installation, maintenance, removal, trafficking), and task (various as shown in Figure 1). Composite and raw data were combined into an overall weighted mean. For the assessment of composite data, when only a range was provided for sample duration, the arithmetic mean of the range was used for the sample. The standard deviation was estimated as the sum of the minimum and maximum values divided by four, when unavailable [52]. A lognormal distribution was assumed in studies with only summary statistics, wherein the arithmetic mean and standard deviation defined the probability distribution for airborne fiber concentration among the raw data. Composite data were summarized by sample type and sample activity.

Airborne fiber concentrations measured by phase contrast microscopy (PCM) or TEM and reported as raw data were classified and analyzed by sample type, sample activity, and by task (Figure 1). Additional analysis included assessment by wet or dry work methods (e.g. soaking tiles prior to removal), and sampling duration (<60 min, 60–240 min, >240 min), as described in the supporting information. The pairwise Wilcoxon rank sum test with the Holm multiple comparison procedure was used to evaluate significant pairwise differences for a given sample classification at a 95% confidence level. The Kaplan–Meier method was used to calculate an upper confidence limit (UCL) for the data set and compared against the ROS method. The data were visualized in the statistical graphing program SigmaPlot XII (Systat Software, Inc., San Jose, CA, USA). The median was determined using randomized raw data.

A final comparison of samples within an individual study was conducted and included evaluations of personal versus bystander samples and personal versus area samples, both conducted using the Wilcoxon rank sum test. A second in-study comparison was made with corresponding PCM versus TEM samples based on their activity, task, method, and sampling duration. Any PCM sample that did not have a corresponding TEM sample was not evaluated and vice-versa. Because of the non-normal nature of the data, natural logs of the PCM and TEM samples were used for the comparison instead of the non-transformed measurements. A linear regression of the paired PCM and TEM samples and a paired *t*-test of the PCM and TEM data were conducted.

Time-weighted average calculation

TWA concentrations (8-h) were calculated for all raw data points assuming the task lasted the length of the reported duration and that the task occurred once per 8-h work day. An airborne fiber concentration of 0 f/cm^3 was assumed for the remainder of the sampling time up to 480 min, or equivalent to an 8-h work day.

Results

A total of 91 records were identified from an online search in addition to a search of our digital repository as being potentially relevant. These studies originated primarily from peer-reviewed publications and published reports. The studies were reviewed based on their titles and abstracts for inclusion of airborne fiber concentrations by sample type, activity, and task. A total of 42 records were deemed relevant. Each study was then reviewed in detail for consideration of inclusion in our quantitative analysis, based on specific inclusion and exclusion criteria. A total of 20 studies were excluded as a result of (1) duplicative data, (2) no sample duration, (3) proximity to an alternate asbestos source (e. g. simultaneous insulation removal), or (4) atypical work practices (Figure 1). A list of all studies considered can be found in Table S1. A total of 22 records were included in our analysis. As seen in Figure 1, raw data were obtained from 17 studies, summary data were obtained from 20 studies, and 8 studies reported 8-h TWA data. Several studies reported both individual and summary data. A list of the studies included in the analysis and the type of data extracted from each is shown in Table 1 and a summary of the worker, bystander, and area air sampling results by PCM, TEM during various work tasks with or around asbestos-containing floor tiles based on meta-data are shown in Table 2.

Analytical techniques

Variable sampling and analytical techniques were reported among the studies included in the analysis. For personal and area samples, total fiber concentrations were most commonly measured using PCM methods recommended by the National Institute for Occupational Safety and Health (NIOSH), including NIOSH methods P&CAM and 7400. In some cases, PCM results were supplemented with additional analyses using TEM methods such as the NIOSH 7402, ASTM D 5755-95, and Chatfield methods. One early study attempted to estimate percentages of asbestos fibers using PCM analysis [45]. Fiber-counting methods included Yamate and AHERA, with the latter method being the most commonly used. To distinguish between fiber types, scanning electron microscopy or X-ray diffraction analysis was used in five studies, all of which identified only chrysotile asbestos [8,16,17,33,42]. In general, most studies were conducted in commercial settings, including, but not limited to, schools, unoccupied commercial buildings, hospitals, and churches. Two studies also investigated airborne asbestos concentrations in residential settings [35,45].

In the current analysis, we evaluated over 1200 individual or summary data points from studies involving floor tiles, including PCM samples of various duration (470 personal, 26 bystander, 295 area) and TWA samples (334 personal, 31 bystander 274 area) were calculated in this current analysis), and TEM samples (139 personal, 2 bystander, and 95 area). Analysis included evaluations by worker group, activities, specific tasks, and by floor tile study. One study published by Kominsky et al. [15]

Table 2. Summary of the worker, bystander, and area air sampling results by PCM, TEM during various work tasks with or around asbestos-containing floor tiles based on meta-data.

	PCM									TEM							
	Sample time (min)		Airborne fiber concentrations (f/cm^3)							Sample time (min)		Airborne fiber concentrations (f/cm^3)					
Task	Min	Max	n	$n_{(detect)}$	Avg.	SD	Min	Max	Task	Min	Max	n	$n_{(detect)}$	Avg.	SD	Min	Max
Baseline	142	480	19	13	0.002	0.002	0.0005	0.007	Baseline	80.5	425	112	65	0.001	0.005	2E − 08	0.05
Installation									Installation								
Area	10	411	25	22	0.02	0.03	0.0006	0.1	Area	10	411	23	14	0.006	0.009	3E − 05	0.03
Bystander	22	411	11	2	0.01	0.009	0.003	0.04	Bystander	32	411	2	0	0.003	0.004	5E − 04	0.006
Personal*	10	411	115	106	0.03	0.05	0.002	0.4	Personal	10	411	6	3	0.4	0.6	6E-05	1.1
Personal TWA*	10	411	59	50	0.01	0.01	0.0002	0.03									
Maintenance									Maintenance								
Area	475	515	5	0	0.0007	0.0003	0.0003	0.001	Area	74	484	31	15	0.07	0.1	2E − 04	0.4
Personal*	43	515	75	62	0.15	0.33	0.002	1.7	Personal*	73	179	105	87	0.0	0.1	5E − 07	0.5
Personal TWA*	43	515	85	72	0.04	0.07	0.0004	0.3									
Personal*(–)	43	515	66	53	0.02	0.04	0.000	0.2									
Personal TWA*(–)	43	515	67	54	0.01	0.01	0.0004	0.05									
Removal									Removal								
Area*	75	393	255	236	0.005	0.006	0.0002	0.07	Area	92	324	41	41	0.004	0.004	2E − 04	0.02
Bystander	101	346	15	15	0.03	0.04	0.003	0.1	Bystander	–	–	–	–	–	–	–	–
Personal*	18	480	280	195	0.03	0.05	0.001	0.4	Personal	52	380	25	16	0.01	0.0	2E − 04	0.0
Personal TWA*	18	480	190	107	0.01	0.02	0.0001	0.2									
Trafficking									Trafficking								
Area	10	300	10	10	0.005	0.006	0.0005	0.02	Area	–	–	–	–	–	–	–	–
Personal	–	–	–	–	–	–	–	–	Personal	30	30	3	1	0.2	0.3	2E − 04	0.5

PCM: Phase contrast microscopy; TEM: transmission electron microscopy; *n*: number of samples; $n_{(detect)}$: number of samples in which asbestos was detected; Avg: average; SD: standard deviation.
*For concentrations reported as structures per cubic centimeter (s/cm^3), it was assumed that 1 s/cm^3 = 1 f/cm^3.
– = No data available.
* = Includes individual and summary data. The absence of (*) implies that only individual (raw) data were used to generate these values.

described airborne asbestos fiber concentrations during UHS burnishing tasks involving floor tiles that were greater than that of tasks reported in other studies. Although the arithmetic mean of the personal samples for concentration and TWA were double in comparison to the summary data excluding Kominsky et al. [15], the medians were only slightly higher. We would not expect that including Kominsky et al. [15], data would affect the Kruskal–Wallis and Wilcoxon test results for comparison between study or worker group because they are nonparametric. Within the analysis by activity and task, however, significant differences existed when the Kominsky et al. [15] data were included, versus when they were excluded. There were no differences in the statistical conclusions for the analysis by worker group, described in further detail below.

Analysis by worker group (personal, bystander, and area samples)

Based on language provided in each of the studies regarding personal involvement or proximity to floor tile work, three worker groups were categorized: personal, bystander, and area (Figure 2). Personal sampling tasks across all activity categories within the raw data averaged 107 min (range 10–515 min) and bystander sampling activities averaged 154 min (range 22–411 min). Bystander distance from source was not defined in most studies. Similarly, area samples were generally in the same room as the floor tile work, but a distance from source measurement was typically not provided.

Personal samples

Overall, the peak PCM personal airborne fiber concentration results were consistently below the current OSHA Short-Term Exposure Limit (STEL) (30 min) of 1.0 f/cm^3. While it was not always possible to differentiate the activity duration from the total sampling duration, comparison with the STEL and PEL was warranted as approximately 24% of the tasks reported were less than or equal to 30 min in duration and 66% were less than or equal to 60 min. As the majority of PCM personal samples were less than 60 min, this value was selected as the group hereafter referred to as "short-term" sample; the details of the statistical differentiation between duration categories are described in the supporting information. Airborne PCM fiber concentrations for personal samples ranged from 0.001 to 1.7 f/cm^3 (arithmetic mean ± standard deviation, 0.05 ± 0.1 f/cm^3) (Table S3). Among the raw data, all of the 52 samples with a reported sampling duration less than or equal to 30 min were below the OSHA STEL. When all sampling durations were compared against the OSHA STEL, all but 4 out of the 218 personal PCM samples were below (sampling duration range 10–515 min) the

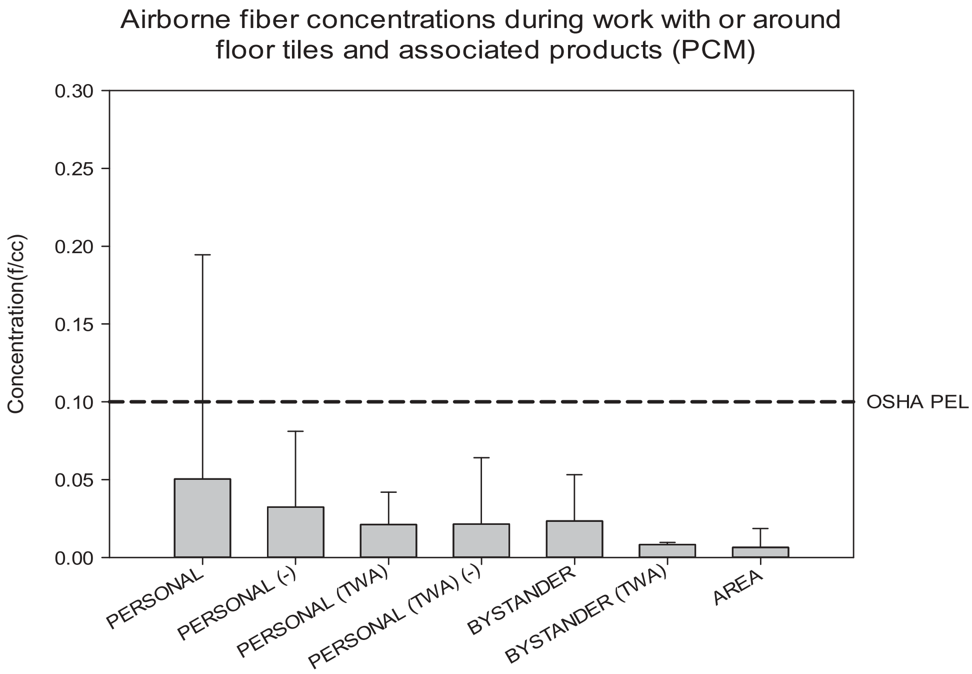

Figure 2. Airborne fiber concentrations during work with or around floor tile and associated materials by working group. Analysis by phase contrast microscopy. The boundary of the box marks the arithmetic mean and the whisker represents the standard deviation. Personal samples are defined as in the breathing zone of a worker. "(–)" represents the data excluding the ultrahigh-speed burnishing samples reported in Kominsky et al. [15] (part II). The definition of a bystander sample differed between studies but generally indicated proximity to the worker. Area samples were taken in the same room where work was being conducted and room size varied between studies. Baseline samples were taken before or after studies and were conducted both indoors and outdoors. Time weighted average (TWA) samples represent an 8-h duration.

current regulatory value. In addition, 96% (N = 209) of all PCM personal concentrations were less than half of the current OSHA STEL. The four samples that exceeded the STEL and those greater than 0.5 f/cm^3 had sampling times that were all greater than 30 min (mean 78 min), and all were sampled during UHS burnishing activities as reported by Kominsky et al. [15].

Similarly, the personal PCM TWA airborne fiber concentrations were also consistently lower than the OSHA PEL. TWAs calculated from both raw and composite data for personal samples ranged from 0.0001 to 0.3 f/cm^3 (arithmetic mean ± standard deviation, 0.02 ± 0.02 f/cm^3). The average 8-h TWA personal airborne fiber concentration was also less than half of the current OSHA PEL of 0.1 f/cm^3.

Bystander and area samples

Personal and bystander samples originating from the same study and the same sampling campaign were compared against each other. In general, the arithmetic mean and median personal samples are about a factor of 3 greater than the bystander samples, across both the short-term samples (bystanders were approximately 35% of personal samples; p = 0.0058) and for the TWA samples (bystanders were approximately 28% of personal samples; p = 0.035) between the two groups based on the Wilcoxon rank sum test. The same results were observed from the comparison between the PCM personal samples and the PCM area samples. The arithmetic mean and median of the personal PCM samples were greater than those for the area samples by about a factor of 3–4 for both short-term (area was approximately 29% of personal) and TWA samples (area was approximately 53% of personal) ($p < 0.00001$ for both personal vs. area and personal vs. area TWA samples). These results are consistent with previously published estimated airborne fiber concentrations near bystanders who stood anywhere from 5 to 10 ft away from work activity involving asbestos-containing materials as reported by Donovan et al. [53].

A relationship between corresponding PCM and TEM data has been shown for previous studies [59]. To compare the PCM and TEM data for the current analysis, the PCM and TEM samples were matched as best as possible from the studies with data from both analysis methods and based on their activity, task, and sampling duration. Any PCM samples that did not have a corresponding TEM sample were not included in the analysis. The natural logs of the PCM and TEM samples were used for this comparison instead of the actual measurements using two types of analyses: a linear regression of the paired PCM and TEM samples, and a paired t-test of the PCM and TEM data. The linear regression analysis indicated that there was a significant trend in TEM concentration based on PCM concentration (log TEM = 0.33 × log PCM −4.8) but the R^2 is extremely low at 0.08 indicating that PCM concentration only explains 8% of the TEM concentration. The results from a paired t-test of the natural logs of the data show that there is a significant difference between the TEM and PCM concentrations for each sample ($p < 0.00001$). The mean difference in the natural logs is 1.8 with a 95% confidence interval of 1.3–2.3. If this difference is transformed back out of log space, this means that the average PCM/TEM ratio is 6.2 (exp(1.8)) and the 95% confidence interval for the PCM/TEM ratio ranges from 3.8 to 10.3. Part of the variability of within the PCM/TEM ratio may have to do with some samples with TEM values far greater than the reported PCM values (e.g. MAS [18]).

Classification of floor tile activities

Personal sample floor tile activities were classified by routine maintenance (e.g. stripping, cleaning, buffing, polishing), installation, and removal activities (Figure 3). Bystander floor tile activities included removal and installation, and activities in the general area of floor tile work included maintenance, installation, removal, and wear or trafficking of tiles (walking across tile or shuffling chairs and desks) [16,17,36].

An overview of the activity classifications by worker group (personal, bystander, area) is shown in Table S4. For the purposes of this study, installation included activities such as drilling, punching, scoring, cutting, or otherwise breaking the tiles. An adhesive or mastic was typically applied and allowed to set for a certain period of time before the tiles were laid by hand [42,54]. Routine maintenance tasks included wet stripping of the existing polish, refinishing (i.e. waxing, polishing), buffing, and burnishing [1,15,54]. Wet stripping typically involved using an alkaline detergent chemical agent and a rotary disk machine operating at up to 300 revolutions per minute (rpm). Both buffing and burnishing processes created a smooth and glossy polished finish by means of friction, while spray-buffing helped to restore polish on a previously finished floor [1]. Rotary disk machines were operated at up to 300 rpm during buffing or spray-buffing processes, and up to 1,100 and 2,000 rpm during high-speed burnishing and UHS burnishing, respectively [15].

Based on our review of the literature, several commonly used removal techniques were performed with a variety of hand and power tools. Hot removal involved heating the tile and mastic using a propane torch, whereas a cold removal involved using dry ice to freeze the tile and mastic; both techniques were intended to render the tile and mastic more easily scraped off [13]. Furthermore, there were some

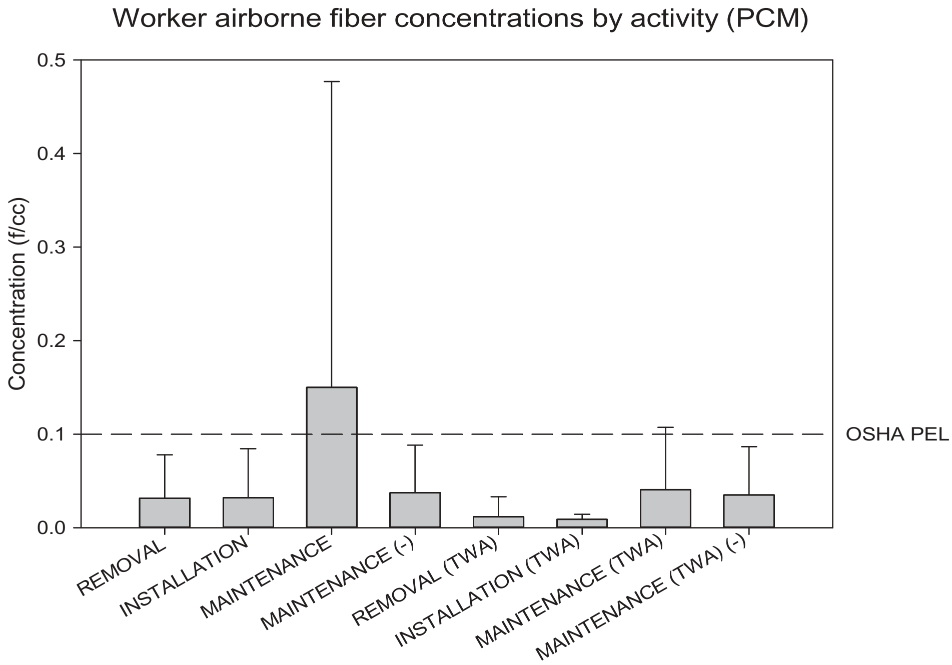

Figure 3. Worker airborne fiber concentrations during work with floor tiles and associated materials by activity. Analysis by phase contrast microscopy. The boundary of the box marks the arithmetic mean and the whisker represents the standard deviation. Personal samples are defined as in the breathing zone of a worker. Only activity results from personal samples are represented. "(–)" represents the data excluding the ultrahigh-speed burnishing samples reported in Kominsky et al. [15] (part II), specific to the maintenance task. Time weighted average (TWA) samples represent an 8-h duration.

instances in which a chemical agent was applied to remove residual mastic [13]. Generally, a hand scraper, described as a heavy duty wall scraper, or hand spud bar was used to remove tile; however, in the event that the tile was difficult to remove, a pneumatic spud bar may have been used [13]. For those peer-reviewed studies that reported data associated with floor tile abatement, activities were generally conducted in ventilated enclosures. Unfortunately, little information regarding ventilation or engineering controls was provided in the unpublished documents.

The majority of the studies reported task-based work activities ranging from 10 to 515 min in duration for personal, bystander, and area samples. As such, 8-h TWAs were calculated from PCM data, based on reported task duration and assuming one task per 8-h work shift, to estimate the concentration during a typical full shift, thereby enabling a comparison of those values to the current OSHA PEL of 0.1 f/cm^3 [55]. Across all studies, installation tasks were significantly greater than trafficking (p = 0.049) but were significantly less than maintenance tasks (p = 0.028). Maintenance tasks were also significantly greater than removal tasks (p = 0.0047).

Classification of floor tile task

In total, 19 personal, bystander, and area floor tile tasks were classified under three activity categories: installation, maintenance, and removal (Figure 1). None of the activities had tasks in common with the exception of the "unspecified" task that appears in the installation, maintenance, and removal activity groups. Fewer categories of floor tile tasks that were available for personal-only samples are described in Figure 4.

In general, based on Holm–Bonferroni pairwise Wilcoxon rank sum tests, three tasks were significantly different among PCM samples. First, the baseline PCM samples were significantly lower than those associated with the buff/burnish, cut, hand tools, strip/refinish, score/snap, scrape/lift, and unspecified task categories. Second, the buff/burnish PCM samples were significantly greater than those associated with the baseline, cut, drill, hole punch, hand tools, machine sand, scrape/lift, strip, trafficking, and unspecified task categories. Finally, with the exception of the buff/burnish category, the unspecified task category had PCM concentrations that were significantly higher than the baseline, clean-up, drill, hole punch, hand tools, machine sand, strip, and trafficking categories. The resulting order of PCM personal airborne fiber concentrations by task, from lowest to highest concentration, including the Kominsky et al. [15] samples, was strip < chemical solvent (mastic) < machine sand < cut (shears, knife) < hand tools < scrub < strip refinish < scrape, lift < unspecified < score, snap < buff, burnish.

Additional comparisons were made by task within each activity group (i.e. task comparisons within the

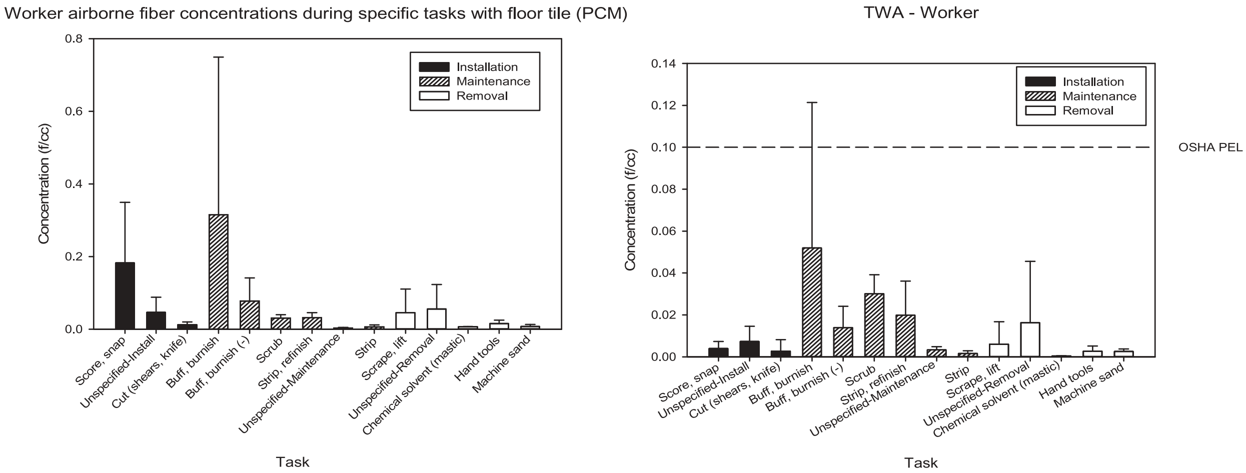

Figure 4. Task-specific worker airborne fiber concentrations during work with floor tiles and associated materials by activity. Analysis by phase contrast microscopy. Includes only personal samples from the raw data set. The boundary of the box closest to zero indicates the 25th percentile, a line within the box marks the median, and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers (error bars) above and below the box indicate the 90th and 10th percentiles. The black dots represent the 5th and 95th percentiles. Sample numbers for each group (*N*): score, snap (6), unspecified (5), cut (shears, knife) (8); buff, burnish (34), scrub (2), strip, refinish (6), unspecified (2), strip (16); scrape, lift (51), unspecified (43), chemical solvent (mastic) (2), hand tools (39), and machine sand (4).

removal group only). The results from these comparisons are shown in the supporting information.

Classification by study

To ensure that there was nothing unusually different about one or more studies included in this analysis, the Kruskal–Wallis test was used to identify any significant differences among the individual studies. This test indicated that there was at least one significant difference between the studies for both PCM and TEM samples ($p < 0.00001$). Of the studies that included PCM raw data, the order from highest to lowest median PCM concentration were as follows: Kominsky et al. [15] > Walcott and Warrick [45] > MAS [18] > Kominsky et al. [8] > Fowler [46] > Lundgren et al. [42] > Lange [19] > Environ Corp. [33] > Lange et al. [38] > Lange and Thomulka [11] > EPI [56] > USACE [20] > Kominsky et al. [1] > Lundgren et al. [16] > Oberta and Fischer [10]. Based on the follow-up pairwise Wilcoxon rank tests (although there are other significant differences between individual studies), the median TEM concentration from Ewing et al. [17] study is significantly greater than every other study except Oberta and Fischer [10] and MAS [18].

Discussion

Asbestos-containing floor tiles are non-friable (cannot be crumbled or pulverized by hand-pressure alone) and the asbestos fibers are considered to be "encapsulated" in the tile or backing matrix [25]. OSHA acknowledged the limited potential for releasing fibers from encapsulated materials in 1972 when encapsulated products were exempted from asbestos labeling requirements if product use did not result in an exceedance of the OSHA PEL for asbestos [26]. The OSHA labeling exemption for encapsulated products remains in effect today [27]. The EPA also drew a distinction between friable and non-friable asbestos products in the early 1970s [28].

In the current analysis, the results from over 45 years of research on airborne exposures associated with the replacement, maintenance, and trafficking activities of floor tiles are described. The creation of a combined data set allowed us to provide results across a wide variety of experimental parameters and make comparisons against any future studies with floor tiles or associated products. The average airborne asbestos concentrations reported in this meta-analysis for both a worker performing floor tile tasks, as well as a bystander working in the vicinity of such activity, were below both the current and all previous US occupational asbestos standards. These results are consistent with those reported by Lange [57] over a decade ago, but those did not break down exposures by activity and task.

The highest PCM concentrations of airborne asbestos were reported for short-duration personal samples during maintenance activities (arithmetic mean 0.15 f/cm^3, range 0.002–1.7 f/cm^3). This sample set, however, included the Kominsky et al. [15] UHS burnishing samples. In an outlier analysis using Rosner's test in ProUCL (1% significance), one potential outlier was identified to be 1.7 f/cm^3, originating from the Kominsky et al. [15] study. Adjusting the Rosner's test to a 5% significance level, we find that all of the nine Kominsky et al. [15] UHS burnishing samples are flagged as potential outliers, in addition to one removal activity sample (task unspecified) from Fowler [46] (range 0.67–1.7 f/cm^3 for all 10 samples). However, the UHS burnishing samples reported by Kominsky et al. [15] were unique within the "buff, burnish" task category of the dataset used in the current analysis in that the authors used dry methods during the UHS burnishing, while the remainder of the samples in this category employed wet methods. Without these nine UHS burnishing samples, the arithmetic mean airborne fiber concentration was calculated to be 0.04 f/cm^3 (range 0.002–0.3 f/cm^3). Since the Kominsky et al. [15] samples represented a unique activity, removing them as outliers was not justifiable.

When the airborne fiber concentrations are compared against national ambient airborne fiber concentrations, the lower bounds of the reported results in the current study overlap with the reported ambient fiber concentrations. For example, mean airborne fiber concentrations ranged from 0.0010 to 0.0022 f/cm^3 in urban environments from the 1960s to the 1990s and maximum fiber concentrations ranged from 0.0037 to 0.05 f/cm^3 [58].

Similarly, the personal TWA maintenance airborne fiber concentrations were calculated to be 0.01 f/cm^3 (range 0.0004–0.05 f/cm^3) without the Kominsky et al. [15] UHS burnishing samples, which are approximately 10 times less than the OSHA 8-h TWA PEL of 0.1 f/cm^3. The average personal TWA concentration including the Kominsky et al. [15] UHS samples was 0.03 ± 0.06 f/cm^3, which is still well below the current OSHA PEL. In total, 10 calculated 8-h TWA samples exceeded the OSHA 8-h TWA PEL of 0.1 f/cm^3. Nine out of 10 of these samples were from the Kominsky et al. [15] study during UHS burnishing tasks, and one was from Fowler [46] during an unspecified removal task using dry methods. Interestingly, the remainder of the 40 unspecified removal TWA samples from Fowler [46] were well below the current OSHA PEL of 0.1 f/cm^3.

Using dry methods for UHS burnishing is not consistent with standard industry practice. As early as 1987, the Resilient Floor Coverings Institute (RFCI), a world authority on commercial, industrial, and residential floor coverings, has published recommended work practices for removing asbestos-containing floor coverings, including sheet vinyl and VAT [32]. Per RFCI's 1987 recommended work practice manual, several general rules are specified regarding the removal of sheet vinyl or VAT:

(1) Unless absolutely positive beyond any doubt that the floor is a non-asbestos product, assume it contains asbestos and treat it in the manner prescribed in this pamphlet for a floor containing asbestos. (2) It is preferred to install a new floor over a floor which contains asbestos rather than to remove that floor. This can be done several methods: new underlayment, use of leveling compounds, and following installation procedures recommended by the floor covering manufacturer. (3) Never sand any resilient floor or its backing to remove them from the floor. (4) All sweeping must be done wet. (5) All scraping must be done wet. (6) Material removed must be placed in heavy-duty polyethylene bags at least 6 mils thick. Properly labeled and disposed of in an authorized land fill. [32]

This issuance by the RFCI was in advance of the EPA's 1989 asbestos ban.

Based on publication date, there was no obvious temporal trend of personal PCM TWA concentrations decreasing or increasing over time. This is not surprising, as several studies collected data over several years or published data that had been collected several years prior. Similarly, there was little discussion in each study regarding the use of control measures, including engineering controls. An interesting follow-up study would be to analyze which control measures seemed to have the largest impact with respect to decreasing airborne fiber concentration (e.g. wetting, exhaust, ventilation).

Although there were very few bystander samples overall (N = 11 installation, N = 15 removal), the bystander samples specific to installation and removal were fairly consistent. The arithmetic mean airborne fiber concentration for bystanders in the vicinity of floor tile installation was 0.01 f/cm^3 (range 0.003–0.04 f/cm^3), while the arithmetic mean in the vicinity of removal was 0.03 f/cm^3 (range 0.003–0.1 f/cm^3). In general, these data do not suggest that bystander exposures to asbestos during installation and removal activities associated with floor tiles exceed the OSHA PEL.

The arithmetic mean airborne fiber concentrations reported for area samples or those in the vicinity of floor tile work (non-bystander) ranged from 0.0002 to 0.1 f/cm^3 (Table S3). The area sample concentrations were, for the majority of all raw data samples (100 out of 105 samples), less than the upper bound of detected ambient asbestos concentrations in urban environments in the United States (range 0.00004–0.05 f/cm^3) [58].

Limitations of this analysis were noted to be (1) the lack of raw data for all available studies, which required using imputed methods to determine overall averages. While every attempt was made to contact study authors on multiple occasions, not all raw data could be obtained; (2) comparison of samples that were analyzed and counted via differing methods, particularly among the TEM samples. The inconsistencies between counting methods employed following TEM analysis has been previously described above and elsewhere [59]; and (3) inclusion of samples that would have otherwise been considered statistical outliers (e.g. Kominsky et al. [15]; MAS [18], described above). The decision was made to exclude two studies (Murphy et al. [48] and Crossman et al. [13]) based on atypical work practices. The first study excluded was Murphy et al. [48], because of its unrealistic and aggressive work practices. In this study, the authors used a coarse-grit belt sander for 20 min on asbestos tiles that had been glued to a piece of wood. Exposures were determined to be 1.2 and 1.3 f/cm^3 by PCM. The second study excluded was Crossman et al. [13]. The authors performed floor tile removal work under experimental abatement practices, such as flooding the room for 3 days, prior to removal [13]. Because of the fact that the practices reported by Crossman et al. [13] were experimental, and so as not to underestimate exposures, these samples were removed from the analysis.

Several additional research questions exist regarding potential asbestos exposures associated with handling asbestos-containing floor tiles. There are very limited data on exposures to mastic associated with floor tile, versus floor tile and mastic exposures combined. There are also limited bystander data; however, as personal exposures to floor tile do not exceed the current OSHA PEL, there is not likely a need for further research associated with bystander exposures. Additionally, the preparation of asbestos air samples for TEM analysis may create problems when assessing asbestos release from tiles. In some cases, solvents can dissolve the asphalt or vinyl polymer-binding asbestos fibers, thereby releasing fibers that were formerly bound in the matrix and would otherwise be uncountable [47]. Although this effect is seen with direct-transfer TEM specimen preparation, it is intensified by indirect TEM specimen preparation techniques involving "ashing," which degrades organic matrix during preparation [47]. Lastly, the majority of exposures related to asbestos-containing floor tiles are associated with vinyl tiles and do not typically include asphalt-asbestos tiles. While the height of asphalt-asbestos and vinyl-asbestos floor tiles overlapped somewhat during the 1950s, the availability of a multitude of patterns and colors among VAT, in addition to their low cost, led to the domination of VAT in the US market [60]. Whether differences exist in exposures between VAT and asphalt-asbestos tiles remains unclear, however.

Overall, the arithmetic mean 8-h TWA airborne fiber concentrations during work with or around asbestos-containing floor tiles during various activities and tasks ranged from 0.01 to 0.02 f/cm^3, based on the results from the current analysis for personal samples including and excluding the Kominsky et al. [15] UHS burnishing samples (Table S3). These concentrations do not exceed the current OSHA PEL of 0.1 f/cm^3. For perspective, over a 45-year working lifetime at these same occupational exposures, the cumulative lifetime occupational dose of asbestos would range from 1.5 to 2.3 f/cm^3 years, assuming 8-h exposures at the arithmetic mean personal airborne fiber concentration from this study, with and without the UHS burnishing data (0.05 and 0.03 f/cm^3, Table S3). This dose is less than half of than the cumulative lifetime dose of asbestos at exposures equal to the current OSHA PEL of 0.1 f/cm^3, or 4.5 f/cm^3 years over a 45-year working lifetime.

In a recent meta-analysis by Pierce et al. [61], "best estimate" chrysotile no-observed adverse effect levels of 208–415 and 89–168 f/cm^3 years for mesothelioma and lung cancer, respectively, were reported [61]. Churg et al. have suggested that, at the very least, the doses of chrysotile necessary to increase the risk of developing asbestosis (25–100 f/cm^3 years) are necessary to increase the risk of developing lung cancer and mesothelioma [62,63]. Any exposures from work with or around asbestos-containing floor tiles would not, under any plausible scenario, approach these threshold values for increased risk of developing an asbestos-related disease.

Conclusions

Exposures associated with handling and using asbestos floor tiles, under conditions normally encountered, have not been shown to produce airborne concentrations at levels that exceed the current OSHA PEL as an 8-h TWA. Any asbestos exposures associated with work with or around asbestos-containing floor tiles do not, under any reasonable or foreseeable use scenario, approach the threshold cumulative asbestos dose concentrations that have been previously associated with an increased risk of developing an asbestos-related disease.

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