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Personal Exposures to Asbestos Fibers During Brake Maintenance of Passenger Vehicles

MARÍA FERNANDA CELY-GARCÍA[1], MAURICIO SÁNCHEZ[1], PATRICK N. BREYSSE[2] and JUAN P. RAMOS-BONILLA[1]*

[1]*Department of Civil and Environmental Engineering, Universidad de Los Andes, Bogotá, Colombia;* [2]*Department of Environmental Health Sciences, Bloomberg School of Public Health, Johns Hopkins University, Baltimore, MD, USA*

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Introduction: Brake linings and brake pads are among the asbestos-containing products that are readily available in Colombia. When sold separated from their support, brake linings require extensive manipulation involving several steps that include drilling, countersinking, riveting, bonding, cutting, beveling, and grinding. Without this manipulation, brake linings cannot be installed in a vehicle. The manipulation process may release asbestos fibers, which may expose brake mechanics to the fibers.

Methods: Three brake repair shops located in Bogotá (Colombia) were sampled for 3 or 4 consecutive days using US National Institute for Occupational Safety and Health (NIOSH) methods 7400 and 7402. Standard procedures for quality control were followed during the sampling process, and asbestos samples were analyzed by an American Industrial Hygiene Association accredited laboratory. Personal samples were collected to assess full-shift and short-term exposures. Area samples were also collected close to the brake-lining manipulation equipment and within office facilities. Activities were documented during the sampling process.

Results: Using Phase Contrast Microscopy Equivalent counts to estimate air asbestos concentrations, all personal samples [i.e. 8-h time-weighted averages (TWAs) and 30-min personal samples] were in compliance with the US Occupational Safety and Health Administration standards. Personal asbestos concentrations based on transmission electron microscopy counts were extremely high, ranging from 0.006 to 3.493 f cm^{-3} for 8-h TWA and from 0.015 to 8.835 f cm^{-3} for 30-min samples. All asbestos fibers detected were chrysotile. Cleaning facilities and grinding linings resulted in the highest asbestos exposures based on transmission electron microscopy counts. There were also some samples that did not comply with the NIOSH's recommended exposure limits.

Conclusion: The results indicate that the brake mechanics sampled are exposed to extremely high asbestos concentrations (i.e. based on transmission electron microscopy counts), suggesting that this occupational group could be at excess risk of asbestos-related diseases.

Keywords: asbestos; brake linings; brake mechanics; chrysotile; Colombia; exposure assessment

INTRODUCTION

Asbestos have been used in brake and friction products since the early 1900s (Paustenbach *et al*., 2004). Occupational exposures to asbestos can occur when asbestos-containing products such as brake and friction products are machined or manipulated.

It is still possible to find brake shoes and pads that contain chrysotile asbestos, particularly in developing countries. Several recently conducted studies from developed countries have concluded that brake mechanics that work on light vehicles

*Author to whom correspondence should be addressed.
Tel: +57-1-339-4949; fax: +57-1-332-4313;
e-mail: jramos@uniandes.edu.co

and small trucks with asbestos-containing products are exposed to asbestos concentrations below the US Occupational Safety and Health Administration Personal Exposure Limit (US OSHA PEL) of 0.1 f cm^{-3} (Hickish and Knight, 1970; Yeung *et al*., 1999; Weir *et al*., 2001; Blake *et al*., 2003, 2006; Paustenbach *et al*., 2003, 2004). These studies conclude that brake mechanics are not at excess risk of developing asbestos-related diseases. In contrast, Finkelstein (2008) suggested that brake mechanics have increased risks of asbestos-associated cancer.

Paustenbach *et al*. (2003) reviewed studies conducted on brake manufacturers and brake mechanics in the USA, the UK, Germany, Sweden, and Australia. The first studies to determine asbestos exposures among brake mechanics were conducted in 1970 and 1972 (Paustenbach *et al*., 2004). Paustenbach *et al*. (2003) reported that the 8-h time weighted average (TWA) asbestos concentrations based on phase contrast microscopy (PCM) for brake mechanics during the 1970s and 1980s ranged between <0.002 and 0.68 f cm^{-3} and depended on the type of vehicle serviced, country, time period, and brake cleaning method (Paustenbach *et al*., 2003).

With the advent of bonded linings and the introduction of disk brakes that use brake pads, the need to drill or grind brake linings was eliminated in the USA beginning in the 1960s (Yeung *et al*., 1999; Paustenbach *et al*., 2003, 2004).

In recent decades, there has been a trend in developed countries to strictly regulate and even ban the use and production of asbestos-containing products (Addison and McConnell, 2008; Lee *et al*., 2008; Ross *et al*., 2008; Wagner and Lemen, 2008).

Among the asbestos-containing products available in Colombia are brake linings and pads (i.e. both imported and locally produced). Major differences exist between the working conditions and procedures conducted in brake repair shops (BRS) in Bogotá, and those observed in developed countries. Since the vehicle fleet circulating in countries such as Colombia is much older than those in developed countries, brake systems that require brake linings are still common. Brake linings require adjustment before installation, and because of this brake mechanics in Colombia have to manipulate brake linings in ways that may result in high asbestos exposures. These practices are no longer common in developed nations. Consequently, the personal asbestos exposure concentrations found in studies conducted in developed countries among brake mechanics may not apply to mechanics in developing countries such as Colombia.

Both environmental and occupational regulations of asbestos are scarce in Colombia. The most important occupational regulation dates from 1979 (Resolution 2400/79) (MTSS, 1979). Although asbestos is not specifically regulated, Colombian Resolution 2400/79 states that any occupational hazard that does not explicitly have a PEL should follow the limits issued by the American Conference of Governmental Industrial Hygienists (ACGIH) (MTSS, 1979). Although this is the case with asbestos, enforcement in Colombia is lax, making verification of compliance of Resolution 2400/79 difficult. In 1998, Colombia ratified Asbestos Convention 162 of the International Labor Organization (Congreso, 1998), but this did not result in modifications of the asbestos occupational standards. Because of the absence of Colombian standards, the results from this study were compared with the US OSHA PEL, the US OSHA Short Term Exposure Limit (STEL), and the US National Institute for Occupational Safety and Health Recommended Exposure Limit (US NIOSH REL). The 8-h TWA OSHA PEL and the ACGIH Threshold Limit Value (TLV) are both set at 0.1 f cm^{-3}.

Production and consumption of asbestos and asbestos-containing products has increased in Colombia in the last decade. In 2002, Colombia occupied 10th place among the world's asbestos producers with 8000 tons $year^{-1}$ (Tossavainen, 2008), and by 2007 Colombia was the sixth largest producer in the world, behind only Russia, China, Kazakhstan, Brazil, Canada, and Zimbabwe (LaDou *et al*., 2010). Currently, one asbestos mine operates in Colombia, in the small town of Campamento, Antioquia.

This article summarizes the results of personal and area asbestos concentrations collected from brake repair and maintenance operations in three BRS located in Bogotá, Colombia.

MATERIALS AND METHODS

BRS that conduct brake repair and maintenance in Bogotá were identified using telephone directories. Out of the 70 facilities listed, 21 expressed initial interest in the study and verbally confirmed that they did brake repairs. Of these BRS, 16 agreed to have a visit from study staff members, and 3 decided to actively collaborate with the project by authorizing asbestos sampling on their premises.

Asbestos sampling was conducted for 3 or 4 consecutive days at each of participating BRS. Both personal and area asbestos samples were collected and analyzed following NIOSH methods 7400 for Phase Contrast Microscopy (PCM) and 7402 using transmission electron microscopy (TEM). TEM provides optical equivalent counts to PCM but has the advantage of classifying fibers by type and/or mineralogical group.

The study was approved by the Ethics Committee of the University of Los Andes, and workers who directly participated in the study signed informed consent forms.

Personal samples were collected to verify compliance with occupational exposure limits. For the purposes of this study, the results were compared with the OSHA PEL of 0.1 f cm^{-3} (8-h TWA) and the OSHA STEL of 1 f cm^{-3} (30 min) using PCM-equivalent (PCME) chrysotile concentrations. Results were also compared against the NIOSH REL which is set at 0.1 f cm^{-3} in 400 L collected over 100 min.

Workers were instructed to conduct their daily activities without modifications to avoid study-induced bias. No requests for changes in normal working procedures and conditions were made by members of the research team. Basic demographic information was obtained from workers, but no health assessments were conducted.

Personal samples were collected using an AIRChek XR5000 pump (SKC-Inc. Eighty Four, PA, USA). Area samples were collected using a LIBRA Plus Personal Sampling Pump (A.P. Buch Inc., Ocala, FL, USA) and a SP280 pump (Air Diagnostics and Engineering Inc., Harrison, ME, USA). Samples were collected on 25-mm MCE filters, 0.45-µm pore size, mounted on 25-mm sampling cassettes equipped with 50-mm conducting extension cowls (SKC Preloaded Cassette, SKC Inc., Eighty Four, PA, USA and Zefon TEM Cassette, Zefon International Inc., Ocala, FL, USA).

All flow rates were measured at the beginning and at the end of the sampling window using a Defender 510 High BIOS International Calibrator (BIOS International, Butler, NJ, USA), following standard procedures. Pumps were operated for at least 5 min with a dummy filter cassette attached before flow was calibrated. If the difference between initial and final flow was greater than 5%, the sample was considered suspect.

Two types of area samples were collected at breathing height (1.5 m) (Blake *et al*., 2009); one was collected at ~2.5 m from the site where brake linings were prepared prior to installation on vehicles (in BRS3 these samples were collected at 1.3 and 3.1 m); and a second was collected at the office facilities of BRS. Blank samples were collected on every sampling day. A background sample was collected from every BRS during one night of the sampling days, when no activities were performed, to establish background concentrations.

Asbestos counts and identification were conducted by an American Industrial Hygiene Association (AIHA) accredited laboratory (RJ Lee Group, Monroeville, PA, USA). Two types of TEM were used for counting, JEOL 1200-EX and JEOL 2000-FX (JEOL USA Inc., Peabody, MA, USA). Counting was conducted at an initial magnification of ×1000 to locate fibers and at ×20000 to measure the dimensions of fibers. The accelerating voltage used was 120 kV. An energy dispersive X-ray (EDXA) (Advanced Analysis Technologies, Mexico D.F., Mexico) was also used. Each microscope was equipped with a detector and analyzer. For counting, the spot size was <100 nm, and the analytical sensitivity was <175 eV, typically closer to 140 eV (RJ Lee Group, personal communication).

All samples were analyzed by both PCM (Method 7400) and TEM (Method 7402). The NIOSH Method 7402 was used to directly calculate optically visible asbestos fiber concentrations and to determine the fraction of optically visible asbestos fibers. According to Method 7402, fibers with a diameter greater than 0.25 µm that meet the same definition of a fiber specified in the Method 7400 are counted by TEM. Using this technique, we counted fibers that would have been counted under phase contrast microscopy (Method 7400). We also determined the optically visible fraction of fibers that are asbestos in order to convert PCM fiber counts into PCM equivalent (PCME) asbestos fiber counts.

When filters were overloaded with fibers, the samples were suspended and re-deposited for analysis. An ultrasonic bath (65w table top model) was used to remove fibers from a piece of filter that had been cut from the original filter. The suspension of fibers was carefully mixed and deposited onto a clean, 25-mm filter that was then prepared for analyses according to NIOSH 7402. When a re-deposition was required, the asbestos concentrations were corrected based on the dilution factor (RJ Lee Group, personal communication).When it was possible, samples were collected for full-shifts in order to estimate the 8-h TWA. In some cases, multiple partial period samples were collected over a full shift to minimize filter overloading. For these workers, TWAs were calculated by time-weighting partial period samples. Descriptive statistical analyses were performed on TEM results according to type of sample (personal 8 h and 30 min) and type of BRS.

BRS were sampled between May and August 2010. BRS1 was sampled between May 25 and 31, 2010; BRS2 was sampled between 8 and 11 June 2010; and BRS3 was sampled between 29 July and 3 August 2010.

All the activities conducted by the mechanics during brake repair and maintenance operations were closely followed and recorded in activity diaries.

Description of brake lining manipulation practices

In Colombia, both asbestos and non-asbestos containing brake linings are sold separately or attached to a shoe (i.e. support). When brake linings are sold separated from the shoe, the brake linings must be manipulated to attach them to the shoe before installation.

Most of the brake linings sold in Colombia for passenger vehicles are classified according to their thicknesses (Table 1). Both asbestos and non-asbestos–containing brake linings follow this classification.

As part of this project, we identified the steps involved in the manipulation of brake linings to prepare them for installation (Fig. 1). The process starts with the removal of the old brake shoe from the vehicle's brake drum. Replacing brakes can involve reusing and relining the existing shoe or installing a pre-lined brake shoe. If the existing brake shoe is to be reused, the old lining needs to be removed. When a new brake shoe with the lining attached is installed, manipulation of brake linings is not required (i.e. identified in Fig. 1 as steps 1–4). If the old shoe is reused, brake shoe preparation depends on how the old brake lining was attached to the shoe (i.e. riveted, bonded, or both, identified as options 1–3 in Fig. 1).

As Fig. 1 shows, the removal of the old brake lining from a shoe can involve the use of an unriveting machine, and/or the separation of the brake lining with a chisel and hammer. Once the lining has been removed, the old shoe must be ground to prepare it for a new lining. This process has the potential to release large amounts of asbestos fibers into the workplace air.

All the BRS participating in this study used the type of asbestos containing brake linings shown in Table 1. BRS2 also carries brake linings in rolls, which require cutting to match the shoe dimensions.

Table 1. Thickness and type of brake linings.

Brake lining type	Commercial thickness specifications (mm)
STANDARD	~0.5
X	~0.7
XX	~0.9

Attaching the new lining to the shoe is done by riveting and/or bonding the lining (Fig. 1), although bonding was only used at BRS2. To bond a brake lining to a shoe, glue is applied followed by heating of the lining and shoe, which may leave excess glue. In these cases, a metal brush is used to remove excess glue, which can release asbestos fibers (Fig. 1). If the lining is too thick, and bonding is insufficient to hold the pieces together, rivets are also added.

Riveting requires drilling holes in the linings and in shoes, which do not already have holes. Drilling holes in the linings is another step that releases asbestos fibers (Fig. 1). Before installing rivets, the lining must be countersunk, which also releases asbestos fibers to the air. Both bonding and riveting are done by riveters. In either case, when linings *X* or *XX* are installed (Table 1), the borders of the lining are beveled. On some occasions, the entire exposed surface of the lining is ground to make it thinner. These procedures, which were common during the study, released the largest amount of asbestos fibers of the entire brake lining manipulation process. Beveling and grinding were done by riveters and/or brake mechanics.

Once attached to the shoe, the edges of brake linings may extend beyond the shoe. In this case, it is necessary to cut or grind the edges to match the lining to the shoe before beveling or grinding.

RESULTS

Description of the BRS

The three BRS participating in this study work mostly with passenger cars and other light vehicles. BRS1 and BRS3 prepare brake shoes exclusively for vehicles that are repaired at their facilities. BRS2 prepares brake shoes for vehicles serviced at their facilities and at other nearby BRS.

BRS1, which works only with asbestos containing brake linings, installs three or four sets of four brake linings per day. Five mechanics work at the shop, with one as a riveter. The facility, ~560 m^2, is completely covered by a roof and no physical barriers separate the area where brake linings are manipulated from the rest of the shop. Office space is located ~40 m from the brake lining manipulation area, close to the shop's entrance. Workers occasionally use filtering face-piece respirators.

BRS2, which works with asbestos and non-asbestos brake linings, installs ~20 sets per day. Two workers are in charge of lining preparation. BRS2 is located on the second floor of a two-story building. Manipulation of brake linings is done in

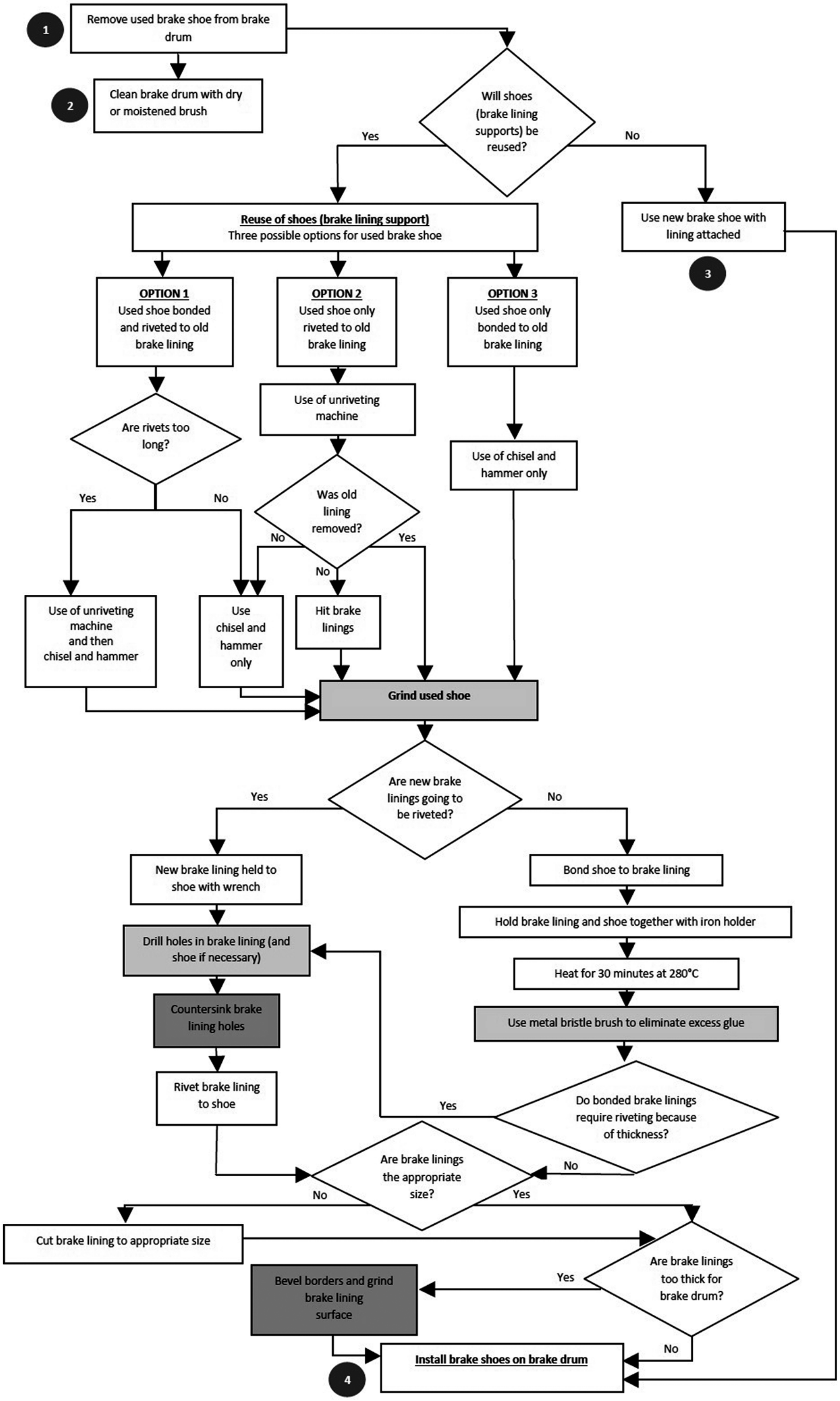

Fig. 1. Steps involved in the manipulation of brake linings.

two adjacent rooms: one measuring ~6.5 m^2 and the other measuring ~8 m^2. Office space is located ~5 m from these rooms on the same floor. Vehicle repairs are done in a separate nearby building. On some occasions, it was observed that when using filtering face-piece respirators, the mechanics only covered their mouth or would remove the respirator when manipulating brake linings.

BRS3, which works with asbestos and non-asbestos brake linings, installs one or two sets per day. This was the only BRS sampled that installed both types of brake linings (separated and preinstalled on shoes). Of the seven workers at this shop, one worked as a riveter. This facility has an area of ~700 m^2 partially covered by a roof. Part of the equipment for brake-lining manipulation is located in a separate room. Grinding equipment is located in a different area of the shop but without physical barriers isolating it from the rest of the shop. Office space is located ~10 m from the grinding equipment and ~9 m from the manipulation room. At this shop, the riveter always used a half face-piece air-purifying respirator. However, he wore it without the recommended asbestos filters, and in any case it did not fit properly because the respirator face piece was broken.

Sampled population

All workers sampled at the three BRS, with one exception, had more than 1 year of experience as riveters. Table 2 shows general demographic information about these workers at the time of sampling.

Air sample results

A total of 57 samples were collected at the three BRS sampled (i.e. 19 long-term personal samples, 15 short-term personal samples, 10 area samples, 10 office samples, and 3 background samples). Additionally, 10 blanks were also analyzed.

Tables 3–5 summarize the asbestos concentrations results from each BRS. The only type of asbestos identified was chrysotile. All TEM fiber counts were above the limit of quantification (LOQ, reported in the case of TEM as 'sensitivity' by the laboratory), except for seven (five from BRS3 and background samples in BRS1 and BRS3). For samples that were below the LOQ, one-half the LOQ was used for calculation purposes. A total of five samples were suspected because the difference between the initial flow and final flow was above 5%.

It was necessary to divide the 8-h work-shifts (480 min) into shorter time windows to reduce the chance of overloading, especially in BRS2. For these samples, we calculated a partial-period TWA (Table 6). For any unsampled time, we assumed that a worker would be exposed to 0 f cm^{-3}. This assumption was made because during non-sampling periods, workers left the shops, work shifts finished early, or workers were not performing tasks that released fibers. Table 6 indicates the time for which 0 f cm^{-3} was assumed for estimation of the TWA 8-h concentration.

Sample overloading was an issue in the first two BSR shops. Fifty percent of the PCM long-term personal samples collected in BSR1 and BSR2 were overloaded and as a result were not able to be counted. Seventy percent of the long-term personal samples collected in BSR1 and BSR2 were overloaded. We were able to count these samples by suspending and re-depositing the samples as described earlier. There is no acceptable method for re-depositing samples for PCM analysis. As a result, the high fraction of overloaded PCM samples makes interpreting these results difficult.

Table 7 summarizes information about personal samples collected and analyzed by TEM. It includes the medians and ranges of asbestos concentrations for each personal sample type. For BRS1, three of the four TWA 8-h personal samples exceeded 0.1 f cm^{-3} based on TEM results. All the samples in

Table 2. General characteristics of workers sampled.

BRS	Worker	Age (years)	Height (m)	Weight (kg)	Principal task	Experience as riveter	Smoke (yes/no/ occasionally)
BRS 1	Worker 1	41	1.72	80	Riveter	22 years	No
	Worker 2[a]	56	1.60	54	Brake mechanic	29 years	No
BRS 2	Worker 3	22	1.65	65	Principal riveter	1.5 years	Occasionally
	Worker 4	42	1.79	86	Auxiliary riveter	22 years	No
	Worker 5	32	1.74	66	Auxiliary riveter	1 day[b]	No
BRS 3	Worker 6	32	1.60	50	Riveter	5 years	No

All information was reported by workers.
[a]Did not manipulate brake linings during sampling.
[b]This was Worker 5's first day as a riveter. Previously, he had been a construction worker.

Table 3. Summary of asbestos concentrations measured at brake repair shop 1 (BRS1).

Type of sample	Sample ID	Sampling time (min)	Total volume (L)	Number of chrysotile fibers	Poisson 95% CI Lower	Poisson 95% CI Upper	TEM concentration (f cm^{-3})	Sensitivity (f cm^{-3})	f(chrysotile fibers)/F(total fibers)	Number of fibers detected by PCM	Limit of quantification[a]	PCM equivalent concentration (f cm^{-3})
Personal samples	Day1 W2 P1[b]	265	713	21.0	13.0	32.1	0.231	0.005	0.933	OL	NC	NC
	Day1 W2 P2	77	207	8.5	3.8	16.4	0.040	0.002	0.378	44.0	0.013	0.037
	Day2 W1 P3[c]	483	1008	38.5	27.3	52.7	0.594	0.008	0.906	OL	NC	NC
	Day3 W1 P4	192	402	87.0	69.7	107.3	0.249	0.001	0.897	100.0	0.007	**0.126**[f]
	Day4 W1 P5	202	424	125.5	196.6	256.4	0.290	0.001	0.875	101.5	0.006	**0.163**[f]
Short-term personal samples	Day4 W1 30 1	35	73	99.0	80.5	120.5	1.514	0.008	0.980	83.0	0.037	0.532
	Day4 W1 30 2	30	64	1.0	<0.04	0.0	0.015	0.008	0.500	12.0	0.042	0.031
Area samples close to manipulation equipment	Day1 A1	208	455	105.5	85.9	127.1	0.505	0.002	1.000	101.5	0.006	**0.187**[f]
	Day1 A2	234	493	15.0	8.4	24.7	0.030	0.001	0.750	17.5	0.005	0.012
	Day2 A3[c]	489	1320	16.0	9.1	26.0	0.188	0.006	0.889	OL	NC	NC
	Day3 A4[d]	441	1197	98.5	80.0	120.0	0.230	0.001	1.015	100.0	0.002	0.043
	Day4 A5	483	1294	39.0	27.7	53.3	0.030	0.001	0.830	40.0	0.002	0.012
Area samples in office space	Day2 O1	480	995	20.5	12.6	31.5	0.020	0.001	0.953	9.0	0.003	0.003
	Day3 O2	481	1023	51.5	38.4	67.6	0.049	0.001	1.062	35.5	0.003	0.018
	Day4 O3	460	979	29.5	19.8	42.2	0.030	0.001	0.694	39.0	0.003	0.013
Background	B[e]	655	1396	0.0	<0.003	0.0	<0.001	0.001	0.000	8.5	0.002	0.000

P: personal; 30: short-term; A: area; O: office; B: background.
W1: Worker 1, W2: Worker 2 (Table 2).
NC: not calculated because of overloading. OL: overloaded sample.
[a]Reported by RJ Lee Group.
[b]Overloaded samples corrected with dilution factor of 0.125.
[c]Overloaded samples corrected with dilution factor of 0.063.
[d]Sample is suspected because of flow drift >5%.
[e]Concentration below the analytical sensitivity limit.
[f]Concentration above NIOSH REL

Table 4. Summary of asbestos concentrations measured at brake repair shop 2 (BRS2).

Type of sample	Sample ID	Sampling time (min)	Total volume (L)	Number of chrysotile fibers	Poisson 95%CI		TEM concentration (f cm^{-3})	Sensitivity (f cm^{-3})	f(chrysotile fibers)/F(total fibers)	Number of fibers detected by PCM	Limit of quantification[a]	PCME concentration (f cm^{-3})
					Lower	Upper						
Personal samples	Day1 W3P1[b]	474	999	91.0	73.3	111.7	0.730	0.004	1.000	NA	NC	NC
	Day2 W3P2[c]	122	256	5.0	1.6	11.7	0.311	0.031	0.714	25.5	0.068	0.035
	Day2 W4P3[d]	126	311	7.0	2.8	14.4	0.721	0.051	0.700	18.0	0.040	0.020
	Day2 W3P4[b]	132	277	38.0	26.9	52.2	1.100	0.014	0.938	NA	NC	NC
	Day2 W3P5	122	259	104.0	85.9	127.1	0.503	0.002	1.000	81.5	0.211	0.154
	Day2 W3P6[c]	123	257	82.0	65.2	101.8	5.077	0.031	1.000	NA	NC	NC
	Day3 W3P7[b]	135	284	41.5	29.8	56.2	1.172	0.014	0.912	19.0	0.046	0.030
	Day3 W3P8[e]	161	338	44.5	32.4	59.6	0.527	0.006	1.000	NA	NC	NC
	Day3 W3P9[b]	152	321	107.0	85.9	127.1	7.630	0.036	1.000	NA	NC	NC
Short-term personal samples	Day1 W4 30 1[b]	33	90	32.0	21.9	45.2	2.861	0.044	1.000	20.0	0.153	0.109
	Day1 W3 30 2[b]	30	82	26.5	17.4	38.7	2.592	0.048	0.914	36.5	0.300	0.200
	Day1 W430 3[b]	33	89	12.0	6.2	21.0	1.077	0.045	0.381	2.5	<0.035	0.005
	Day1 W3 30 4[e]	30	65	62.0	47.5	79.5	3.842	0.031	0.961	43.5	0.458	0.317
	Day2 W4 30 5	35	86	104.5	85.9	127.1	1.619	0.008	1.000	37.0	0.291	0.210
	Day2 W4 30 6	36	85	94.5	76.4	115.6	1.928	0.010	0.945	57.0	0.449	0.309
	Day3 W5 30 7[b]	31	69	25.0	16.2	36.9	6.088	0.121	0.240	54.0	0.522	0.092
	Day3 W3 30 8[b]	33	73	36.5	25.6	50.4	4.030	0.055	0.973	69.0	0.634	0.454
	Day3 W3 30 9[b]	31	65	72.0	56.3	90.7	8.835	0.062	1.000	42.5	0.442	0.319
Area samples close to manipulation equipment	Day2 A1	127	314	91.5	73.7	112.3	0.468	0.003	0.901	54.0	0.116	0.076
	Day3 A2[b]	243	541	29.5	19.8	42.2	0.437	0.007	0.937	9.0	0.012	0.008
Area samples in office space	Day1 O1[b]	482	985	95.5	77.3	116.7	0.778	0.004	0.985	49.5	0.034	0.024
	Day2 O2	499	1048	49.0	36.3	64.8	0.047	0.001	0.772	35.5	0.022	0.013
	Day3 O3	567	1151	40.5	29.0	55.0	0.035	0.001	0.764	39.5	0.023	0.013
Background	B[b]	801	1657	3	<0.006	0.0	0.015	0.002	0.857	14.5	0.006	0.004

P: Personal, 30: Short term, A: Area, O: Office, B: Background.
W3: Worker 3, W4: Worker 4, W5: Worker 5 (Table 2).
NA: not analyzed, too heavy; NC: not calculated because of overloading.
[a]Reported by RJ Lee Group.
[b]Overloaded samples corrected with dilution factor of 0.125.
[c]Overloaded samples corrected with dilution factor of 0.063.
[d]Overloaded samples corrected with dilution factor of 0.0313.
[e]Overloaded samples corrected with dilution factor of 0.250.

Table 5. Summary of asbestos concentrations measured at brake repair shop 3 (BRS3).

Type of sample	Sample ID	Sampling time (min)	Total volume (L)	Number of chrysotile fibers	Poisson 95% CI		TEM concentration (f cm^{-3})	Sensitivity (f cm^{-3})	f(chrysotile fibers)/F (total fibers)	Number of fibers detected by PCM	Limit of quantification[a]	PCME concentration (f cm^{-3})
					Lower	Upper						
Personal samples	Day1 W6P1	482	1012	101.0	85.9	127.1	0.192	0.001	0.995	14.0	0.003	0.005
	Day2 W6P2	382	809	6.0	2.2	13.1	0.007	0.001	0.444	9.0	0.003	0.002
	Day3 W6P3[b]	154	327	0.0	<0.0	0.0	<0.002	0.002	0.000	5.5	0.008	<0.008[c]
	Day3 W6P4	108	241	45.0	32.8	60.2	0.189	0.002	0.978	18.0	0.011	0.033
	Day3 W6P5[b]	93	199	0.0	<0.009	0.0	<0.003	0.003	0.000	3.5	0.014	<0.014[c]
Short-term personal samples	Day1 W6 30 1	31	69	100.0	81.4	121.7	2.551	0.013	1.000	54.0	0.039	0.363
	Day2 W6 30 2[d]	30	63	102.5	85.9	127.1	3.631	0.018	1.000	66.5	0.043	0.511
	Day2 W6 30 3	32	67	26.5	17.4	38.7	0.399	0.008	0.964	16.5	0.040	0.113
	Day3 W6 30 4	32	69	19.0	11.4	29.7	0.279	0.007	0.950	12.0	0.039	0.071
Area samples close to manipulation equipment	Day1 A1	370	830	4.0	1.1	10.2	0.005	0.001	0.800	4.0	0.003	0.000
	Day2 A2[e]	481	1076	43.5	31.5	58.5	0.327	0.004	0.946	28.0	0.003	0.012
	Day3 A3	111	249	5.0	1.6	11.7	0.020	0.002	1.000	0.0	0.011	<0.011[c]
Area samples in office space	Day1 O1[f]	480	898	16.0	9.1	26.0	0.018	0.001	0.914	4.0	0.003	0.000
	Day2 O2[bf]	201	427	0.0	<0.003	0.0	<0.001	0.001	0.000	5.5	0.006	<0.006
	Day2 O3[bf]	244	513	0.0	<0.003	0.0	<0.001	0.001	0.000	2.5	0.005	0.000
	Day3 O4[bf]	367	748	0.0	<0.003	0.0	<0.001	0.001	0.000	5.0	0.004	<0.004[c]
Background	B[b]	901	1908	0.0	<0.003	0.0	<0.001	0.001	0.000	3.0	0.001	0.000

P: Personal, 30: Short term, A: Area, O: Office, B: Background.
W6: Worker 6 (Table 2).
[a]Reported by RJ Lee Group.
[b]Concentration below the analytical sensitivity limit.
[c]This concentration is lower than the limit of quantification.
[d]Sample is suspected because it was transferred between workers.
[e]Samples corrected with a dilution factor of 0.125.
[f]Sample is suspected because of flow drift >5%.

Table 6. Personal 8-h time-weighted average TEM and optical equivalent asbestos concentrations.

BRS	Sample ID	Number of sampling windows	Sampling time (min)	Time assumed with 0 f cm^{-3} to complete the 8-h sampling time (min)	TEM concentration for original sampling time (f cm^{-3})	PCME concentration for original sampling time (f cm^{-3})	TEM concentration (TWA 8-h) (f cm^{-3})	PCME concentration (TWA 8-h) (f cm^{-3})
BRS 1	Day2 W1P3	1	483	0	0.60	NC[a]	0.60	NC[a]
	Day3 W1P4	1	192	288	0.25	0.13	0.10	0.05
	Day4 W1P5	1	202	278	0.30	0.16	0.12	0.07
	Day1 W2PTWA	2	342	138	0.20	NC[ab]	0.13	NC[ab]
BRS2	Day1 W3P1	1	474	6	0.73	NC[a]	0.72	NC[a]
	Day2 W3PTWAa	4	499	0	1.74	NC[ac]	1.81	NC[ac]
	Day3 W3PTWAb	4	479	1	3.50	NC[ad]	3.49	NC[ad]
	Day2 W4P3	1	126	354	0.72	0.02	0.19	0.01
BRS3	Day1 W6P1	1	482	0	0.19	0.01	0.19	0.01
	Day2 W6P2	1	382	98	0.01	0.002	0.01	0.002
	Day3 W6PTWA	3	355	125	0.06	0.01[e]	0.04	0.01[e]

W1: Worker 1, W2: Worker 2, W3: Worker 3, W6: Worker 6 (Table 2).
Sample ID according to Tables 3–5.
[a]Not calculated because of overloading.
[b]Partial period TWA estimated with samples Day1W2P1 and Day1W2P2 (Table 3). Sample Day1W2P1 was overloaded. PCME concentration calculated using sample Day1W2P2 (sampling time 77 min) was 0.037 f cm^{-3}. The PCME concentration calculated for a TWA of 8 h for sample Day1W2P2 assuming 0 f cm^{-3} in the time remaining to complete 8 h was 0.006 f cm^{-3}.
[c]Partial period TWA estimated with samples Day2W3P2, Day2W3P4, Day2W3P5, and Day2W3P6 (Table 4). Samples Day2W3P4 and Day2W3P6 were overloaded. The PCME concentration calculated with samples Day2W3P2 and Day2W3P5 (sampling time 244 min) was 0.095 f cm^{-3}. The PCME concentration calculated for a TWA of 8 h for samples Day2W3P2 and Day2W3P5 assuming 0 f cm^{-3} in the time remaining to complete 8 h was 0.048 f cm^{-3}.
[d]Partial period TWA estimated with samples Day3W3P7, Day3W3P8, Day3W3P9, and Day3W3309 (Table 4). Samples Day3W3P8 and Day3W3P9 were overloaded. The PCME concentration calculated with samples Day3W3P7 and Day3W3309 (sampling time 166 min) was 0.084 f cm^{-3}. The PCME concentration calculated for a TWA of 8 h for samples Day3W3P7 and Day3W3309 assuming 0 f cm^{-3} in the time remaining to complete 8 h was 0.029 f cm^{-3}.
[e]Partial period TWA estimated with samples Day3W6P3, Day3W6P4, and Day3W6P5 (Table 5).

Table 7. TEM statistics summary for all BRS sampled.

Type of sample	Number of samples greater than 0.1 or 1 f cm^{-3} (total number of samples)			Asbestos concentrations for all brake repair shops (f cm^{-3})		
	BRS 1	BRS 2	BRS 3	Median	Min	Max
8-h TWA personal sample—Table 6	3(4)	4(4)	1(3)	0.189	0.006	3.493
Personal short-term sample—30 min	1(2)	9(9)	1(3)[a]	2.240	0.015	8.835

[a]Only valid samples.

BRS2 had full-shift exposures (based on TEM) that exceeded 0.1 f cm^{-3}. In BRS3, one of the three full-shift personal samples exceeded (based on TEM) 0.1 f cm^{-3}. The overall median full-shift asbestos fiber concentration based on TEM was 0.189 f cm^{-3}.

Personal short-term samples and activities

Activity diaries kept by members of the research team during the sampling process made it possible to link air asbestos concentrations with activities performed by mechanics during the collection of personal 30-min short-term samples. Activity-based sampling with both TEM and PCME asbestos concentrations is summarized in Table 8.

DISCUSSION

This study documents elevated asbestos exposures in brake repair shops in Colombia. Based on TEM counts of optically equivalent fibers, 73% (8 out of 11) of the full-shift samples exceeded 0.1 f cm^{-3}. To the best of our knowledge, this is the first study to assess asbestos exposures of brake mechanics conducted in Colombia. Moreover, this study contains

Table 8. Summary of personal short-term concentrations and activities.

Sample	TEM concentration (f cm^{-3})	PCME concentration (f cm^{-3})	Sampling time (min)	Activities
Day4 W1 30 2	0.015	0.031	30	Dry sweeping of floor with a broom in the area surrounding a stack of old asbestos containing brake parts that were going to be moved.
Day3 W6 30 4	0.279	0.071	32	–Unriveting used brake linings from shoes.–Drilling, countersinking, and riveting a new set of four non-asbestos brake linings.
Day2 W6 30 3	0.399	0.113	32	–Drilling, countersinking, and riveting two standard asbestos containing brake linings (Table 1).–Vehicle brake system maintenance.
Day1 W430 3[a]	1.077	0.005	33	–Using a metal bristle brush to eliminate excess glue from brake shoe.–Removing four old brake linings.–Another worker (W3) grinding brake linings close to sampled worker (W4).
Day4 W1 30 1	1.514	0.532	35	Dry sweeping floor with a broom in area surrounding brake lining manipulation equipment.
Day2 W4 30 5	1.619	0.210	35	–Cutting brake linings from rolls.–Removing old brake linings from shoes.–Grinding used shoes after old brake linings were removed.
Day2 W4 30 6	1.928	0.309	36	Drilling, countersinking, and riveting a set of four asbestos containing brake linings. After that, W4 cut linings into the appropriate sizes.
Day1 W6 30 1	2.551	0.363	31	–Removing rivets attaching used brake linings to shoes.–Complete manipulation[b] of two *X* asbestos containing brake linings (Table 1).
Day1 W3 30 2[a]	2.592	0.200	30	–Using metal bristle brush to eliminate excess glue from brake shoe.–Cutting, grinding, and beveling bonded brake linings.–Cutting and grinding asbestos brake linings to the appropriate size for a motorcycle.
Day1 W4 30 1[a]	2.861	0.109	33	–Using metal bristle brush to eliminate excess glue and grinding bonded brake linings.–Another worker (W3), close to sampled mechanic (W4), removed old brake linings from a different set of used brake shoes and ground used shoes for reuse.–Cutting a roll of asbestos brake linings.
Day2 W6 30 2[c]	3.631	0.511	30	–Unriveting used brake linings.–Grinding old shoes for reuse.–Complete manipulation[b] to prepare two *X* asbestos containing brake linings (Table 1).
Day1 W3 30 4[d]	3.842	0.317	30	–Dry sweeping floor with a broom in brake lining preparation area.–Dusting brake lining manipulation equipment with a brush.
Day3 W3 30 8[a]	4.030	0.454	33	–Complete manipulation[b] plus cutting to prepare two *X* asbestos containing brake linings (Table 1).–Worker (W3) blew dust off the surface of manipulation equipment.–Unriveting old brake linings and grinding used shoe from a different set of brake shoes.
Day3 W5 30 7[a]	6.088	0.092	31	–Cutting and grinding to prepare *XX* asbestos containing brake linings.–Unriveting old brake linings and grinding used shoes from a different set of used brake shoes.
Day3 W3 30 9[a]	8.835	0.319	31	–Dry sweeping shop floor with a broom.–W5 dumped the content of a trash can into a garbage bag close to W3.–W3 dry sweeping floor surrounding both the trash can and the garbage bag.–Preparation of brake pads.–Cutting an asbestos sheet to bond brake pad to a brake pad support.–Shaking work clothes while wearing them.

W1: Worker 1, W3: Worker 3, W4: Worker 4, W5: Worker 5, W6: Worker 6 (Table 2).
[a]Overloaded samples corrected with dilution factor of 0.125.
[b]Complete handling includes drilling, countersinking, riveting, beveling and grinding brake linings.
[c]Suspected sample due to transfer of pump and filter between workers.
[d]Overloaded samples corrected with dilution factor of 0.250.

the first detailed description in the scientific literature regarding the process of manipulating asbestos containing brake linings.

Although several recent studies of brake mechanics in developed countries have found asbestos concentrations in compliance with OSHA standards (Hickish and Knight, 1970; Yeung *et al*., 1999; Weir *et al*., 2001; Blake *et al*., 2003, 2006; Paustenbach *et al*., 2003, 2004), of these studies only Blake et al. (2003, 2006) report TEM ratio fiber counts for a limited number of samples (not all samples contained asbestos fibers).

Only a few samples collected in this study exceeded 0.1 f cm^{-3} based on PCME counts. Because of high indoor particle concentrations, several filters obtained during sampling were overloaded, which prevented us from estimating PCME counts. Nevertheless, TEM results make it clear that this group of mechanics could be exposed to high asbestos concentrations. Moreover, in Table 6 samples Day2W3PTWAa and Day3W3PTWAb had sampling windows for which the sample was overloaded. Calculating the TWA with the remaining samples that were not overloaded resulted in a PCME 8-h TWA of 0.095 f cm^{-3} for Day2W3PTWAa and a PCME 8-h TWA of 0.084 f cm^{-3} for Day3W3PTWAb (see also footnotes c and d following Table 6), which are extremely close to the OSHA standard. Additionally, when comparing against the NIOSH Recommended Exposure Limit (REL) (0.1 f cm^{-3} in 400 L), three samples in BRS1 had PCME concentrations that exceeded this limit (Table 3 samples Day3W1P4, Day4W1P5, and Day1A1). In general, PCME asbestos concentrations short-term personal samples were below the OSHA STEL. It should also be noted that all asbestos fibers identified were chrysotile.

Staff at all the BRS indicated that workloads on sampling days were not unusual, although the owners of BRS1 and BRS3 explained that they have had larger workloads in the past. While the results reported in this study are limited to the activities of brake mechanics on the days sampled, we believe the exposures experienced on these days are representative for normal work days of this group of brake mechanics.

The TEM results obtained in this study highlight a number of important points:

First, as the practices for manipulation of asbestos-containing brake linings described in this study have not been used in developed countries for decades, the results from this study can aid efforts that are underway in various countries to retrospectively quantify historical asbestos exposures in this occupational group.

Second, as previous studies in developed countries have concluded that brake mechanics do not seem to be exposed to asbestos concentrations above the occupational standards, and most of these studies only conducted PCM fiber counts, it seems that the exposure levels and potential health risks faced by brake mechanics in developing countries have been underestimated.

Although all fibers identified were chrysotile asbestos, it should be noted that the International Agency for Research on Cancer (IARC) classifies both types of asbestos, chrysotile and amphiboles, as carcinogenic to humans (IARC, 1998). Moreover, regulatory agencies such as OSHA do not make distinctions between types of asbestos fibers in their occupational standards (OSHA, 2010).

The asbestos concentrations found by TEM in the sampling campaign suggest that riveters and brake mechanics have the highest exposures and are therefore at the greatest risk of developing asbestos-related diseases. Furthermore, asbestos concentrations found in other shop areas, including office areas, indicate that administrative staff and customers are also exposed to asbestos fibers and are also at risk of developing asbestos-related diseases. While exposures in the office and other areas may have been below the 0.1 f cm^{-3} threshold, this does not eliminate the potential risk faced by administrative staff and customers from asbestos exposure as OSHA explains that compliance with its 0.1 f cm^{-3} PEL does not eliminate the risk of asbestos-related diseases (OSHA, 1995).

There were important differences of air asbestos concentrations and personal exposure levels among the three shops. These differences may be explained because shops differed in both the number of brake linings manipulated and in the physical characteristics of the facilities.

BRS2 has the highest asbestos concentrations for all types of samples as it has the largest workload and worst ventilation conditions of the three BRS sampled. In BRS2 brake linings were manipulated for both its own customers and for customers of other shops, and this activity was continuously performed at this shop throughout the working day. In contrast, BRS1 and BRS3 only manipulated brake linings sporadically during the sampled days, and they limited work to vehicles serviced at their facilities. This difference in the quantity and continuity of manipulations could help explain differences in asbestos concentrations and is consistent with previous observations by Hickish and Knight (1970) that linked workload measured in the number of brake systems repaired with increased air asbestos concentrations (Hickish and Knight, 1970).

BRS3 had the least brake lining manipulation activities of the three BRS. Moreover, its shop's facilities are open and have plenty of natural ventilation. Thus, it would be reasonable to expect to find all samples from this facility to be lowest. Nevertheless, several 8-h and 30-min concentrations from both the working environment and personal samples indicated high levels of chrysotile asbestos fibers. The results from this facility suggest that lower workloads and plenty of natural ventilation do not provide sufficient protection to completely reduce asbestos exposure.

During sampling it was possible to determine the extent to which mechanics use personal protective equipment (PPE) in these facilities. None of the workers used PPE during all the tasks in which asbestos-containing brake linings were manipulated, and none used PPE recommended for asbestos. Although PPE may provide immediate protection for workers, PPE are at the bottom of the hierarchy of control options for worker protection. Future control interventions should focus primarily on the source.

It should be noted that sample Day3W6304 (Tables 5 and 8) collected during the manipulation of non-asbestos brake linings contained chrysotile asbestos (albeit below OSHA STEL). As this was the first brake lining manipulation of the day, possible explanations are that the equipment may have been contaminated with asbestos fibers from a previous manipulation or that asbestos fibers in dust, which had settled the previous day, may have been resuspended into the air during manipulation of these non-asbestos linings.

Despite our efforts to prevent overloading, air asbestos concentrations were so high on some occasions, especially at BRS2, that some filters became overloaded. For this reason, several samples could not be analyzed by PCM limiting the utility of using PCME counts for risk assessment purposes. The additional manipulation of the filters required for TEM analysis introduces uncertainty regarding the asbestos concentrations and asbestos fiber counts for these samples. Asbestos concentrations for several samples not analyzed by PCM were shown to be extremely high when analyzed by TEM.

As the brake shops sampled represent ~4% of the BRS operating in Bogotá, and sampling was conducted only for 3 or 4 days in each shop, representativeness of sampling could be questioned. Nevertheless, it is important to highlight that these shops represent a range of BRS workload and facility characteristics and that the price ranges and ages of the vehicles owned by customers targeted by each shop varied primarily due to differing socioeconomic statuses of the neighborhoods where the BRS are located. The BRS sampled were also in different geographic locations in the city. We feel that these results represent a cross-section of brake repair activities and thus support generalization of the results for shops that service passenger vehicles. The fact that all three participating BRS had overloaded samples that prevented us from estimating PCME concentrations suggests a need for additional sampling campaigns.

Although several recent studies of brake mechanics in developed countries have found asbestos concentrations in compliance with OSHA standards (Hickish and Knight, 1970; Yeung *et al*., 1999; Weir *et al*., 2001; Blake *et al*., 2003, 2006; Paustenbach *et al*., 2003, 2004), the facilities involved in those studies did not perform the extensive manipulation of brake linings observed in this study. In fact, the tasks done by the mechanics described in those studies appear to include only tasks 1–4 (Fig. 1) when brake shoes are not reused, whereas most of the brake repairs observed in this study involved reuse of brake shoes. This could explain the differences in findings between this study and other recent studies. In addition, it should be noted that studies conducted a few decades ago when brake lining manipulation was still a common practice in developed countries reported air asbestos concentrations exceeding current OSHA standards (Hickish and Knight, 1970; Richter *et al*., 2009).

One problem for comparing the results of this study with previous studies is that most of the studies conducted in the past focused the sampling on the task of cleaning the brake drum (i.e. there was no manipulation of the linings). Furthermore, most of the previous studies relied on PCM for asbestos counting, and because of the low asbestos concentrations found, no TEM was applied. Thus, there is very limited historical information for this occupational group in terms of asbestos concentrations analyzed by TEM.

It is important to highlight that brake linings are manipulated in BRS in Bogotá because they are sold detached from the shoe (i.e. support) and without predrilled holes. To install these linings, they need to be attached to the shoes using a multiple step process that requires physically transforming brake linings (Fig. 1). Although shops have various options for attaching linings to shoes, all options can potentially release asbestos. Thus, the main cause of the asbestos concentrations measured in this study is the decision of brake lining manufacturers to sell linings detached from shoes without prefabricated holes.

Paustenbach *et al*. (2003, 2004) explain that the need to manipulate brake linings was reduced in USA first by the introduction of bonded brake linings in 1948 and then further by introduction of factory-supplied, tapered, and bonded brake replacements in 1950 (Paustenbach *et al*., 2004). Since the 1960s, brake repair and maintenance in USA has been limited to cleaning brake parts with compressed air or brushes and replacing entire brake shoes (Paustenbach *et al*., 2003). Manipulation of passenger vehicle brake linings as currently practiced in Colombia is something that has not occurred in the USA since that time.

Our results suggest that cleaning of floors and surfaces, and grinding and countersinking of brake linings, produce the highest concentrations of airborne asbestos. This is consistent with the results from Richter *et al*. (2009), who did a review of previous studies that measured short-term personal asbestos concentrations during brake cleaning and manipulation between 1968 and 2000. Most of the machining was done during brake maintenance for heavy trucks and buses because brake shoes for passenger vehicles and light trucks do not need any kind of manipulation. The authors reported that the activities that released the most fibers were beveling and grinding without exhaust controls (Richter *et al*., 2009) similar to the findings in this study.

The activities associated with personal short-term asbestos concentrations (Table 8) indicate that exposure to asbestos results from the direct manipulation of asbestos containing brake linings and also from secondary exposures to the asbestos fibers released from the manipulation process, which deposit on the floor and other surfaces, and then can be resuspended again during other activities. In fact, some of the highest personal short-term asbestos concentrations observed using TEM were associated with cleaning activities and not the direct manipulation of the linings.

Finally, in Colombia both asbestos and non-asbestos brake linings are sold and brake linings attached to brake shoes are commercially available. Thus, it seems possible for local companies to manufacture and supply non-asbestos brake linings attached to the shoe, which do not require manipulation.

CONCLUSIONS

This study shows that in Colombia brake linings are still commercialized in a physical form that requires manipulation before installation. As this study's results indicate, manipulations release the asbestos contained in these products. The results indicate that, although the mechanics sampled are only exposed to asbestos concentrations in compliance with OSHA standards, several samples analyzed by TEM showed extremely high air asbestos concentrations. Moreover, high air asbestos concentrations resulted in filter overloading for several samples, which prevented accurate PCM fiber counts and calculation of PCM equivalent counts needed for direct comparison against OSHA standards.

It is likely that Colombia is not alone in this problem, since developing countries in general tend to have weak institutions and regulations to protect the public and occupational groups against hazardous substances. Currently, more than 50 countries worldwide have asbestos bans and restrictions in place. The results from this study suggest that Colombia should seriously consider joining the group of nations that ban and/or restrict asbestos.

Finally, this study brings attention to the deplorable and unacceptable working conditions that some brake mechanics are currently experiencing in developing countries.

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