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Intervention to reduce gymnast exposure to flame retardants from pit foam: A case study

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ABSTRACT

Gymnasts can have high exposures to flame retardants (FRs), which are used in gymnastics safety equipment such as the loose foam pit. Therefore, we aimed to reduce gymnast exposure to FRs by replacing the foam in the pit using foam free of additive FR and measuring personal exposure during practice using hand-wipes. To assure maintenance of fire safety we first conducted a flammability study and facilitated a fire inspection for our partner gym. The FR-treated cubes had similar heat release rates to the non-FR treated cubes, required a 11 cm larger flame size applied for 6 s longer to ignite, and took 4 min longer to reach peak flame height. Based on these findings and the presence of other fire safety measures including smoke detectors and a sprinkler system, the local fire and building departments approved replacement of the foam pit with FR-free foam. We then replaced foam in the gym's pit, verified it was free of any additive FRs, and quantified common halogenated and organophosphate FRs on hand-wipes collected from ten collegiate gymnasts before and after practice, pre- and post-intervention. We observed a 5-fold decline in the median mass of FRs found in pit foam that accumulated on hand-wipes during practice among gymnasts who used the foam pit ($p = 0.02$), indicating that replacing the foam in a pit using materials free of FRs can reduce gymnast exposure to these chemicals during practice.

1. Introduction

U.S. collegiate gymnasts have disproportionately high exposures to flame retardant (FR) chemicals compared to the general population, with serum concentrations similar to those who are occupationally exposed (Carignan et al., 2013a; Carignan et al., 2016). This appears to be due to the large amount of FR-containing polyurethane foam in the gymnastics training environment (gyms). We previously identified FRs in 89% of foam samples from pit cubes collected from 8 gyms in the U.S. (Carignan et al., 2016). Foam samples contained percent by weight (> 10 mg/g) concentrations of FRs and dust concentrations in a sample of U.S. gyms were an order of magnitude higher than concentrations measured in other indoor environments (Carignan et al., 2013a). Another U.S. study reported higher concentrations of FRs in air and dust from gyms compared to the homes of coaches (La Guardia and Hale, 2015). Crumbling foam constituted a large proportion of the dust in the foam pit and other areas of the gym, and this 'pit dust' is known to adhere to the skin (Carignan et al., 2013a). The foam pit appeared to be an important source of FRs to the gym environment as concentrations in dust and air were substantially higher in and near the foam pit

Abbreviations: BEH-TEBP, bis(2-ethylhexyl) tetrabromophthalate; EH-TBB, 2-ethylhexyl-2,3,4,5-tetrabromobenzoate; FM550, Firemaster® 550; ITPs, isopropylated triaryl phosphate isomers; MDL, method detection limit; MPP, methylated phenyl phosphates; PBDE, polybrominated diphenyl ether; PentaBDE, commercial mixture that includes the lower brominated PBDEs; PUF, polyurethane foam; SG, specific gravity; TBPPs, tris-isobutylated triphenyl phosphate isomers; TCIPP, tris(1-chloro-2-propyl) phosphate; TCEP, tris(chloroethyl) phosphate; TDCIPP, tris(1,3-dichloro-2-propyl) phosphate; TPHP, triphenyl phosphate

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compared to other parts of the gym.

Due to their semi-volatile properties, FRs can also volatilize from foam and deposit in dust and organic surface films, including the skin, and enter the body (Stapleton et al., 2009; Allen et al., 2008). FRs are ubiquitous in most indoor environments due to their use in consumer products such as the casings of electronics and foam of upholstered furniture (Watkins et al., 2012; Carignan et al., 2013b). The primary exposure routes for the general population include inhalation, dermal exposure, and incidental dust ingestion (Allen et al., 2007; Watkins et al., 2011; Abou-Elwafa Abdallah et al., 2016) and a recent study estimated that inhalation can be an important exposure pathway for gymnast for organophosphate FRs used in foam equipment (La Guardia and Hale, 2015).

Some of the FR chemicals used in gymnastics training equipment are endocrine disrupting chemicals that have been shown to disrupt thyroid hormone action in the body (Meeker and Stapleton, 2010; Patisaul et al., 2013; Farhat et al., 2013; Wang et al., 2013). Thyroid hormone is important for development and metabolism, and dysregulation of thyroid hormone homeostasis can cause a number of health problems. Both animal and human studies have reported decreased fertility with exposure to polybrominated diphenyl ethers (PBDEs), tris (1,3-dichloro-2-propyl)phosphate (TDCIPP) and triphenyl phosphate (TPHP) (Farhat et al., 2013; Liu et al., 2013; Wang et al., 2015; Farhat et al., 2014; Meeker et al., 2013; Carignan et al., 2017; Harley et al., 2010) whereas prenatal exposure to these FRs have adverse effects on offspring growth (Harley et al., 2011; Chao et al., 2007; Lignell et al., 2013; Foster et al., 2011; Lopez-Espinosa et al., 2015; Moser et al., 2015) as well as pubertal (Patisaul et al., 2013) and neurodevelopment (Gascon et al., 2012; Roze et al., 2009; Evidence on the Carcinogenicity of Tris(1,3-dichloro-2-propyl) Phosphate, 2011), and have been associated with preterm birth (Hoffman et al., 2018). TPHP, a component of several FR mixtures, is a suspected obesogen that can stimulate development of fat cells and interfere with bone cell development (Pillai et al., 2014; Belcher et al., 2014). In addition to its impact on fertility and thyroid hormone regulation, TDCIPP is a genotoxic carcinogen (CalEPA, 2015) and a potential developmental neurotoxicant (Dishaw et al., 2011).

Given these health concerns it is precautious to limit exposure to these FRs, particularly during sensitive windows of development from preconception through the child bearing years. Gymnasts are a vulnerable population because of the potential for high exposures and because training in the gym environment is prevalent during childhood and adolescence. The majority of U.S. gymnasts are under the age of 18 and 76% are female. Competitive gymnasts have intense practice schedules in the years preceding and immediately following puberty, spending 15–20 h/week in the gym (Carignan et al., 2013a). Gymnastics is a popular sport with over 6 million gymnasts training at > 4000 clubs in the US. While most participate recreationally (> 4 million) a substantial number of gymnasts train frequently (1.8 million training > 50 days/year) or competitively (> 900,000 training > 100 days/year) (About USA Gymnastics, n.d.; SGMA's Olympic Top 20 Participation Study, 2017).

Gymnast exposure to FRs in foam training equipment is likely widespread due to preferential purchasing of equipment treated with FRs due to concerns about fire safety. However, the fire safety benefit of FRs in foam training equipment has not been quantified, and the popular fire safety standard California Technical Bulletin 117 was recently updated for upholstered furniture to eliminate the need for additive FRs in foam after reassessment identified little fire safety benefit (Babrauskas et al., 2011; Shaw et al., 2010). Therefore, we conducted both a fire safety and intervention study to test our hypotheses that fire safety can be maintained in a gym without the use of FRs and that replacing the foam in a pit using foam free of additive FR would reduce gymnast exposure during practice.

2. Methods

2.1. Fire safety

To inform design of the flammability testing we first reviewed available data on fires in U.S. gymnastics training facilities. The National Fire Protection Association (NFPA) database was searched using the term ‘gym’, returning 5 records of which only one was for a gymnastics training facility. Due to this low return we also conducted a search of U.S. newspapers using Factiva from 1996 to 2012. This search returned 150 records of which 10 were for gymnastics training facilities. We abstracted information from the 11 records to calculate fire statistics including the year, month, city, state and name of the gym where the fire occurred, cause of fire, and extent of damage. Names of the gym owner, fire chief, and reporter were also recorded and contacted by study staff when information on the fire cause and extent of damage were not provided in the article. This search identified eleven fires in U.S. gymnastics training facilities from 1996 to 2012, with most having occurred at night. The most common source of fires was arson (27%) followed by welding (18%), electrical (9%), and cigarette (9%). Most fires were reported as severe (73%) with fewer significant (18%) or minor (9%) (Supplemental material, Fig. S1). These data were used to inform selection of ignition sources for the flammability testing.

To evaluate the flammability of different types of foam cubes, we conducted flammability testing using three commercially available foam cube material Systems and two types of ignition sources. We tested each combination of Systems and ignition sources in replicates of three. System 1 used a foam cube containing the additive FR that we identified as Firemaster 550® (FM550), and is commonly used in gym foam pits. System 2 used a foam cube without any FR treatment and System 3 used the same cube from System 2 with a nylon fabric cover. These were selected as possibilities for use in our intervention study; the fabric cover was included as it is commonly used in gyms to slow deterioration of the foam. We confirmed that each system contained FR or were free of additive FRs as indicated with independent testing of additive FRs as described in Section 2.2.3. All cubes were 15.24 cm on each side. The two ignition sources tested were a smoldering cigarette and a small methane flame from a Bunsen Burner. We developed test methods using a combination of a modified standard test method and test set-ups that represent possible ignition sources and situations the cubes may be in when in a gymnastics pit. Test methods were modified from procedures to test the fire safety of upholstered furniture, California Technical Bulletin 117 (TB117, 2000) and California Technical Bulletin 117–2013 (TB117, 2013) (Technical Bulletin 117, 2000; Technical Bulletin 117-2013, 2013). The first test method was a small flame test that applied a flame from a standard Bunsen Burner. The single cube tests were used with this method to identify the Super-Critical condition: the smallest ignition source that would cause each System to continue to burn even after the ignition source is taken away from the cube. The second test method was a smolder test using a NIST SRM1196 Standard Cigarette (SRM 1196 - Standard Cigarette for Ignition Resistance Testing, 2012) that was modified from California Technical Bulletin 117 – 2013 (TB117, 2013) (Technical Bulletin 117-2013, 2013). None of the tests included any other materials or components that may be part of a gymnastics pit or other equipment that may be next to the pit cubes. Tests were conducted using a single cube as well as 70 cubes in a small-scale pit. Each test was video recorded to allow flame heights to be measured. All tests are summarized below with additional detail in the Supplementary material.

2.1.1. Single cube

For the cigarette smolder test, a standard test cigarette was lit and placed against the bottom edge of the foam cube System, which sat on a calcium silicate board. The cigarette was allowed to smolder until it went out, over a 20 to 25-minute duration.

For the small flame test an individual foam cube was placed on a piece of calcium silicate board with one edge hanging 13 mm over the front edge of the board. The board was mounted such that the front-bottom edge of each cube was 19 mm above the top of the Bunsen Burner. The initial round of tests had a 38 mm flame height so that half of the flame was directly applied to the front of the cube from the bottom for 12 s, with half of the flame in contact with the cube. If it continued to burn after the flame was removed the burning was allowed to continue for 150 s after the flame was initially introduced to the cube. After 150 s the cube was extinguished with water to get a mass loss rate. Each cube was weighed before and after each test. Flame exposure was increased in intensity systematically until a 'Super-Critical' flame height and duration for consistent ignition was identified. The increase was achieved by first exposing the cube to the flame for longer periods of time by adding 6 s to the exposure time until the exposure time reached 30 s. After 30 s of flame exposure the part of the cube directly exposed to the flame or in the immediate area around the flame had burned or melted away and no longer reacted to the flame from the Bunsen Burner. A second increase in the flame exposure was then introduced by increasing the flame height to 76 mm tall, twice the original flame height. The flame was then applied to the cube for 6 s, 12 s, 18, 24, and 30. This pattern was continued through increasing flame heights until a Super-Critical condition was found.

2.1.2. Small scale pit

We constructed a small scale pit out of gypsum board with the dimensions of 0.9 m by 0.9 m and 0.6 m tall (0.5 cubic meter volume) with an open top. The cigarette smolder and small flame test was conducted for the small scale pit using each combination of foam cube System. Each test used 70 foam cubes to fill the pit to the top, with only one test performed for each System due to limited supply of cubes. One cube at the top of the pile was ignited in the same manner as the single cube test at Super-Critical conditions. Each test was allowed to reach burn out when no significant visible flames remained in the pit.

2.1.3. Heat release rates

A material's heat release rate (HRR), or heat power output, is the driving force for heat, smoke production, and transport through buildings; and is therefore the key parameter indicating its hazard. HRRs were calculated for the small scale pit tests using the following standard equation (Drysdale, 1985):

$$H = 0.23 * HRR^{0.4} - 1.02 * D$$

where H = flame height (m), HRR = Heat Release Rate (kW), and D = Hydraulic Diameter (m).

HRRs for the small scale pit were estimated from flame height measurements during each test using the following equation, with the hydraulic diameter estimated based on the pit length of 0.92 m:

$$HRR = \left[\frac{(H + 1.02 * D)}{0.23}\right]^{2.5}$$

2.2. Intervention study

2.2.1. Foam pit replacement and sampling

We replaced foam in the pit of our partner gym using foam purchased directly from a major pit cube supplier who stated the foam was free of any additive FRs. That statement was specifically requested because the CertiPUR® designation does not assure the absence of all additive FRs. Prior to replacement, we collected foam samples from old foam cubes in the pit (n = 2, one of each color) as well as from the replacement foam cubes (n = 2). Each sample was wrapped individually in aluminum foil, sealed in a zip bag, and shipped to Dr. Stapleton's lab at Duke University for analysis of additive FRs known to be used in polyurethane foam, as described in Section 2.3.3. The old foam was removed and disposed of by a licensed waste disposal contractor under the waste code MA99 – which identifies it as a non-hazardous waste. However, to ensure the FR chemicals were not emitted to the air through incineration, disposal at a lined land fill was requested to best control the potential release of the FR chemicals to the environment. The pit was vacuumed by the waste disposal contractor and the vacuum dust was collected and disposed of with the cubes. However, some cube remnants and dust remained in the bottom of the pit that was inaccessible due to the presence of a trampoline suspended over the bottom of the pit (for added bounce and to reduce the volume of pit cubes needed) which the team was unable to remove. The edges and trampoline bed of the pit were wiped down with Simple Green® All Purpose Cleaner.

2.2.2. Participants and hand-wipe sampling

We recruited a convenience sample of 15 collegiate gymnasts (11 female, 4 male). To be eligible for participation, gymnasts had to be older than 18 years in age, training at the intervention gym, and available to participate on one of the sampling dates. Harvard T.H. Chan School of Public Health's Office of Human Research Administration approved the study protocol. All participants provided informed consent prior to participation, and completed a questionnaire at each sampling time-point reporting his or her demographics, gymnastics history, habits, and training activities as well as recent hand-washing and lotion use. Cotton wipes (MG Chemicals Wipe) for the hand-wipe sampling were pre-cleaned in Dr. Stapleton's lab by extraction with 1:1 hexane:acetone for 24 h, decanting, and air drying on aluminum foil for 24 h before individually wrapping in foil using cleaned forceps and stored in a zip bag. Hand-wipe sampling occurred before and after a mid-week practice in November 2016 and April 2017, pre- and post-intervention, respectively. Under the instruction and supervision of study personnel, each participant used a cotton pad soaked in isopropyl alcohol (99% pure) to wipe the palms of both hands from wrists to finger tips, including between the fingers. Each hand-wipe sample was wrapped in aluminum foil and sealed in a zip bag. Study personnel collected three field blanks using the described protocol, while wearing nitrile gloves and without wiping hands. Hand-wipe samples were stored in a cooler on ice for < 24 h and remained frozen at $-20\,^{\circ}C$ until analysis.

2.2.3. Extraction and FR analysis

Foam samples were tested using gas chromatography–mass spectrometry (GC–MS) under previously published methods (Stapleton et al., 2012; Stapleton et al., 2011) for the presence or absence of FRs that are commonly applied to polyurethane foam including PentaBDE (a commercial mixture of lower brominated PBDEs), TDCIPP, tris(1-chloro-2-propyl) phosphate (TCPP), tris(chloroethyl) phosphate (TCEP), a mixture of tris-isobutylated triphenyl phosphate isomers (TBPP), a mixture of isopropylated triaryl phosphate isomers (ITPs), the chlorinated organophosphate mixture V6, and components of Firemaster® 550 (FM550; a mixture of EH-TBB, BEH-TEBP, TPHP, and ITPs). Positive detection of a flame retardant in foam was defined as $> 0.1\%$ by weight, with the presence of each FR reported qualitatively (Detection = Yes/No). Chromatographs were examined for the possible presence of untargeted additive FRs. For the hand wipe samples, field and laboratory blanks were extracted alongside the hand-wipe samples using previously published methods (Phillips et al., 2018) and data were blank corrected using the average levels measured in the field blanks. Hand-wipe samples were analyzed using gas chromatography negative chemical ionization mass spectrometry (GC/ECNI-MS) for halogenated flame retardants, and gas chromatography electronic impact mass spectrometer (GC/EI-MS) for organophosphate flame retardants as previously described (Carignan et al., 2013a). The extract for one sample was lost during processing, therefore data for this participant (female) was excluded from the data analysis.

2.2.4. Data analysis

We calculated demographic characteristic summary statistics for the pre- and post-intervention study populations as well as summary statistics for FRs detected in hand-wipe samples. Results were examined for outliers in relation to exposure characteristics including whether a participant reported wearing nail polish, using hand lotion, washing hands during practice, or training on bars on a sampling day. We then summed the mass of FRs in each hand-wipe sample that were identified in samples collected from the pre-intervention foam pit (Σfoam pit FR) and those that were not (Σnon-foam pit FR). We then calculated the mass of ΣFRs accumulated on hands during practice as the difference in summed masses on hand-wipes for each participant from before to after practice, and generated summary statistics. We evaluated data for normality both visually and using the Shapiro-Wilk test, and accordingly applied the non-parametric Wilcoxon rank sum test to test for a difference from pre- to post-intervention in the mass of ΣFRs on hand-wipes accumulated during practice. We then applied the Wilcoxon signed rank test whether the mass of ΣFRs on hand-wipes accumulated during practice was different from zero at each of the pre- and post-intervention time-points. Statistical tests were conducted for all participants as well as restricted to those who reported using the foam pit that day during practice. All statistical analyses were performed using SAS (version 9.4; SAS Institute Inc., Cary, NC) with statistical significance defined as $p < 0.05$.

3. Results

3.1. Fire safety

Our flammability study considered two ignition sources spanning the range of those noted for gym fires, three Systems of foam cubes that reflect those used in gyms, and scenarios to understand fire behavior both for a single foam cube and propagation among many.

3.1.1. Single cube

The Super-Critical condition identified for Systems 2 and 3 (foam cubes free of additive FR) was a 38 mm flame applied for 18 s whereas a larger 152 mm flame applied for 12 s was identified for the FR-containing System 1, which contained additive FR. There was no flame observed for any of the Systems with the cigarette smolder test and char patterns were similar. Each System was tested six times and all tests lasted 20–25 min.

3.1.2. Small scale pit

The HRR grew much slower for System 1 and peak HRR was 83% of the System 2 peak and 70% of the System 3 peak (Fig. 1).

For the FR-containing System 1 the flame spread very slowly for the first 5.5 min, however once one of the cubes below the top layer started to burn the fire spread much more rapidly across the top half of the pit. By 7.5 min the pit was fully involved and continued to burn with a 2.4–3.6 m flame height until 10.0 min into the test. At 10.0 min the fire began to die down and continued to burn in the bottom of the pit until flame out at 14.2 min.

For System 2, which was free of additive FR, there was little fire spread for the first minute of the test after which the fire grew exponentially until a peak HRR of 1500 kW at 3.0 min. The fire continued to burn at this maximum until 5.3 min when it quickly died down, with only a few small flames lingering in the bottom of the pit until flame out at 10.2 min.

For System 3, which was free of additive FR and had a nylon cover, the fire spread very slowly at first after which it quickly escalated to a very large fire, 3.0–3.6 m tall, that burned very rapidly. It died down after 5.5 min and then continued to burn the rest of the fuel for another 5.0 min. All three test Systems resulted in approximately 100% of the fuel being consumed.

3.2. Intervention study

3.2.1. Foam samples

FRs identified to be present in foam samples collected from two cubes in the pre-intervention foam pit included TDCIPP in one of the samples and components of the FM550® mixture (EH-TBB, BEH-TEBP, and TPHP) in the other. No additive FRs were identified in foam samples collected from two cubes in the post-intervention foam pit.

3.2.2. Study population

Our study population included 14 participants. A total of 10 gymnasts participated in each of the pre- and post-intervention sampling events, of which 6 participated in both. Each participant was 18–34 years of age and currently trained on the same collegiate team. The majority were female. Over half reported training on bars and/or into the foam pit during practice. Demographic and exposure characteristics were similar for participants pre- and post-intervention (Table 1). Practice on the sampling days lasted approximately 2 h.

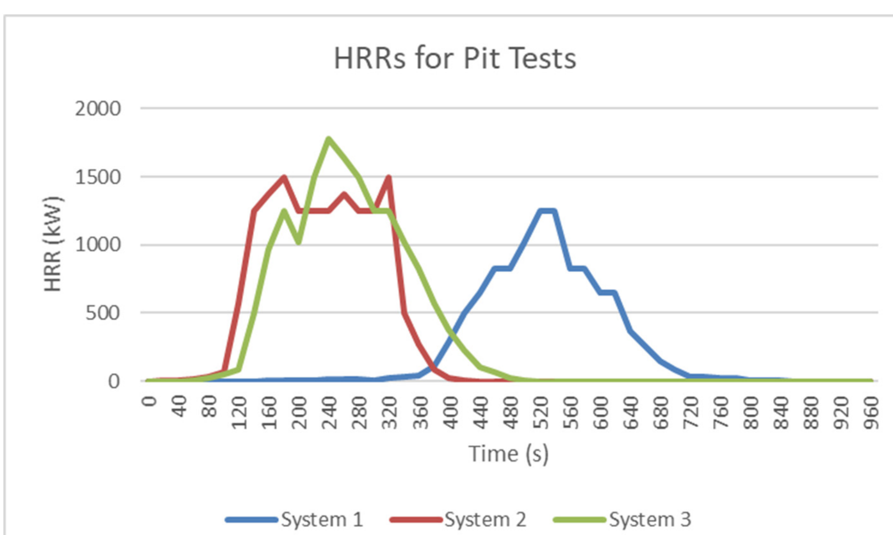

Fig. 1. Heat release rates (HRR) for the small scale pit test by System. System 1 contained flame retardants, System 2 was free of additive FR, and System 3 was free of additive FR and had a nylon cover. kW = kilowatt, s = seconds.

Table 1
Demographic and exposure characteristics for the 14 gymnasts in the intervention study, median (IQR) or N (%).

Characteristic	Pre-intervention (n = 10)	Post-intervention (n = 10)
Age, years	19 (19, 20)	20 (19, 21)
Body mass index, kg/m^2	23.7 (22.7, 24.6)	23.4 (22.7, 24.0)
Female	8 (80)	6 (60)
Years as a gymnast	14.5 (13, 17)	14.5 (14, 18)
Wearing nail polish	2 (20)	0 (0)
Hours since last hand wash	1.5 (1, 2)	2 (2, 2)
Used lotion before practice	1 (10)	0 (0)
Washed hands during practice	1 (10)	1 (10)
Trained on bars during practice	7 (70)	5 (50)
Trained into foam pit during practice	5 (50)	7 (70)
Typically eats during practice	1 (10)	1 (10)
Typically eats after practice	3 (30)	4 (40)

3.2.3. Hand-wipes

We identified quantifiable levels of each of the measured FRs in 100% of hand-wipe samples (Supplementary material Tables S2–S3). No outliers were identified in relation to exposure characteristics including whether a participant reported wearing nail polish, using hand lotion, washing hands during practice, or training on bars on a sampling day. Based on results of the foam sample testing we summed FRs in hand-wipe samples that were identified pre-intervention in samples from the foam pit (Σpit FRs = TDCIPP, EH-TBB, BEH-TEBP, TPHP) and those that were not (Σnon-pit FRs = TCEP, TCIPP, BDE17, BDE28/33, BDE47, BDE66, BDE100, BDE99, BDE85/155, BDE154, BDE153, BDE138, BDE183, BDE209). The mass of FRs accumulated on hands during practice was calculated by taking the difference of the mass on hand-wipes from before to after practice.

From pre- to post-intervention we observed a 5.4-fold decline in the median mass of Σpit FRs accumulated on hands during practice among those who reported using the foam pit ($p = 0.02$, $n = 8$) (Fig. 2). This difference was smaller and marginally non-significant considering all participants (3.3-fold, $p = 0.06$, $n = 10$). Prior to the intervention, the GM mass of Σpit FRs increased 4.5-fold from before to after practice among participants who reported using the foam pit ($p = 0.06$, $n = 5$), with a smaller 2.7-fold increase when restricted to those who provided samples both pre- and post-intervention ($p = 0.03$, $n = 6$) (Fig. 3, Table 2). No differences were observed for Σnon-foam pit FRs (Supplementary material Figs. S1–S2, Table S3). These results indicate that replacing the foam in a pit using foam free of additive FR was effective at reducing gymnast exposure to FRs from the foam pit.

Post-intervention there was a non-significant 1.4-fold increase in the GM mass of Σpit FRs from before to after practice ($p = 0.16$, $n = 10$) and a significant 2-fold increase among participants who reported using the foam pit ($p = 0.03$, $n = 7$). These results indicate the presence of other sources of FRs in the gym, which may include landing mats, carpet bonded foam, and residual FRs from the pre-intervention foam pit.

4. Discussion

4.1. Fire safety

We found that both FR treated and non-FR treated cubes resisted smolder ignition but produced severe fires when exposed to ignition sources of small flames or larger, and we observed no benefit of the nylon fabric cover. These results are typical for flexible foams used in buildings, indicating that foam materials in general have the potential to negatively affect fire safety if ignition sources other than small open

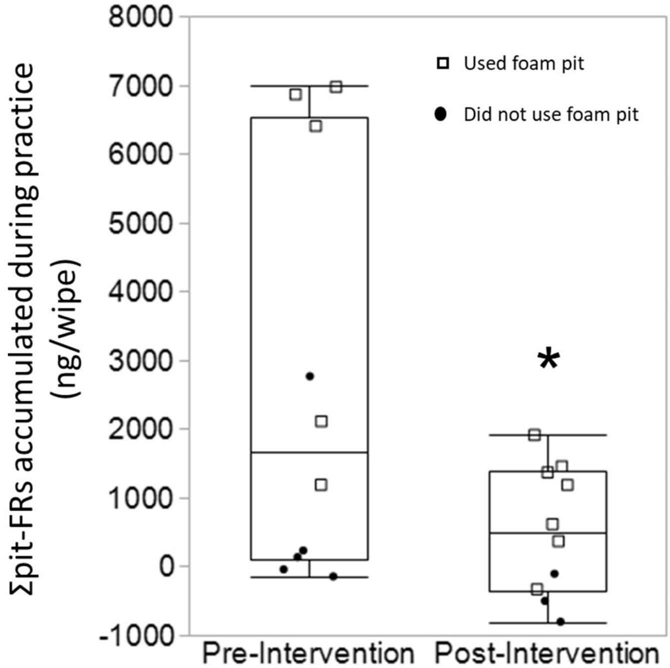

Fig. 2. The mass of Σpit FRs accumulated on hands during practice as measured on hand-wipes collected pre- and post-intervention of replacing the foam in a pit using foam free of additive FR. *Statistically significant difference from pre- to post-intervention (Wilcoxon rank-sum).

flames are present. Our findings are also consistent with the data we compiled on gym fires, which indicate that when gym fires occur they can be severe and result in total loss of the gym. Therefore, gyms should consider holistic building performance for fire safety including fire detection systems, fire suppression systems such as sprinklers, posted and clear egress routes, configuration of the foam pit(s) relative to the rest of the building, building geometry such as ceiling height and egress pathways, and fire drill training. These recommendations are consistent with standard practice in fire safety and promote fire safety without the use of additive FR chemicals. More details of the flammability testing and results are provided as Supplementary material.

Our partner gym hired an independent fire protection engineer (FPE) to review our gym fire statistics, data from our flammability study, and to inspect the gym for fire safety. The FPE made general recommendations to ensure fire safety including fire evaluations plans, fire notification pull stations, and a monitored sprinkler system. Based on our data and the FPE report, the local fire and building departments approved replacement of the foam pit with foam free of additive FR. We also developed a guidance document and checklist for gyms considering replacing their foam pits using foam free of additive FR (Supplementary material). The checklist is intended to assist gym owners and fire departments considering fire protection measures for facilities with foam pits.

4.2. Intervention study

Our finding that replacing the foam in the pit reduced accumulated FRs on gymnast hands is consistent with a previous study of gymnastics coaches, which found a reduction in FRs on handwipes with replacement of a pit that had PentaBDE in the foam (Supplementary material Fig. S4 and Table S4) (Ceballos et al., 2018; Broadwater et al., 2017). That study also found that the replacement foam contained other halogenated and organophosphate FRs, therefore it is important to specify that foam should be free of any additive FR.

While the intervention was effective at reducing the GM mass of FRs accumulated on hand-wipes during practice observed residual

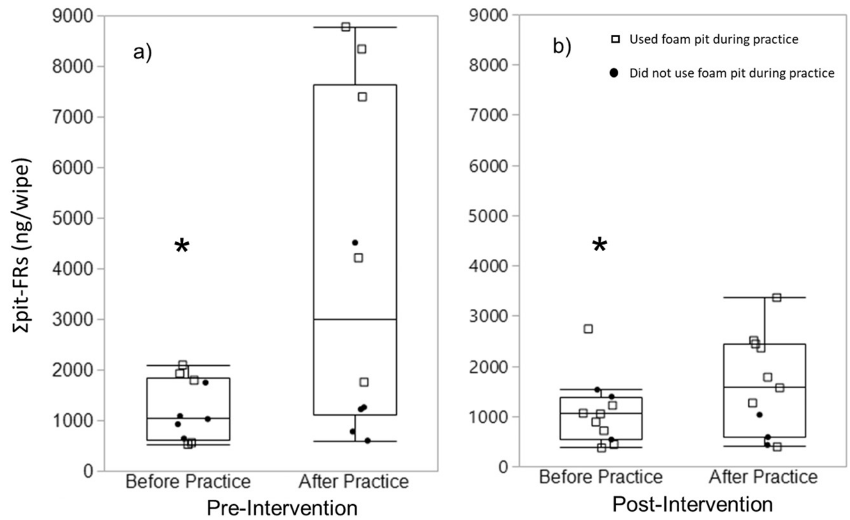

Fig. 3. The mass of Σpit FRs measured on hand-wipe samples collected pre- and post-intervention of replacing the foam in a pit using foam free of additive FR. *Statistically significant difference from before to after practice (Wilcoxon signed-rank).

accumulation post-intervention. This is likely due to FRs in the foam of other gym equipment, as we previously found evidence of brominated FRs in landing mats and carpet-bonded foam (Carignan et al., 2013a).

The GM mass of FRs that accumulated on hands pre-intervention were an order of magnitude higher than the general population (Hammel et al., 2016; Hoffman et al., 2014; Hoffman et al., 2015) (Supporting Information Fig. S3 and Table S5), a finding that is consistent with our previous studies reporting elevated gymnast exposure. The GM mass on gymnast hand-wipes was also modestly elevated before practice for pit-FRs and other FRs used in foam [TCIPP, TDCIPP, TPHP, EH-TBB, and BEH-TEBP], which may reflect increased use of these FRs in the foam of upholstered furniture over the past decade (Stapleton et al., 2012; Hoffman et al., 2017).

While hand-wipes are a useful exposure biomarker (Phillips et al., 2018) it is unclear how accurately they can be used to estimate total gymnast exposure as dust ingestion rates for gymnasts are unknown. We expect that gymnast exposure via incidental dust ingestion and dermal absorption, important exposure pathways for FRs in other indoor environments (Watkins et al., 2011; Cequier et al., 2014), may be higher than the general population due to suspension of dust particles during training activities, increased dermal loading due to direct dermal contact with foam and dust, and increased dermal absorption due to increased permeability from perspiration. We also expect primary exposure routes to the FRs measured in this study differ by class; for example inhalation and dermal exposures may be more important for TPHP and TDCIPP due to higher vapor pressures and dermal permeability compared to PBDEs and EH-TBB (U.S. Environmental Protection Agency, 2005; Hughes et al., 2001; Pawar et al., 2016).

While gymnast exposure to FRs is expected to be elevated in gyms that have FRs in foam equipment, the mixture of FRs that gymnasts are exposed to during practice likely varies widely between gyms depending on the age and amount of foam equipment. We previously reported a higher prevalence of PentaBDE in pit foam purchased prior to its phase out in 2005 in samples collected from gyms across the U.S. whereas foam purchased post-phase out was more likely to contain replacements such as TDCIPP or components of FM550® (EH-TBB, BEH-TEBP, TPHP) (Carignan et al., 2016). It is important to quantify and consider exposure to these mixtures as we recently reported potential cumulative effects of the organophosphate FRs (TDCIPP, TPHP, and mono-ITP) on the success of couples' fertility treatment (Carignan et al., 2017).

Gymnast exposure is also expected to vary based on personal factors such as handwashing and time spent in the gym. Competitive gymnasts can train for over 20 h per week starting at a young age. During this

Table 2
Flame retardants on hand-wipes collected before and after practice, pre- and post-intervention of replacing the foam in a pit using foam free of additive FR.

	Before practice GM (95% CI)	After practice GM (95% CI)	Fold difference from before to after	Median difference (p-value)
All apparatus				
Pre-intervention (n = 10)				
Pit-FR	1097.3 (753.2, 1598.6)	2577.4 (1242.9, 5344.8)	2.35	1658 (0.01)
Non pit-FR	217.7 (123.8, 382.8)	188.4 (130.1, 272.7)	0.87	−55 (0.32)
Post-intervention (n = 10)				
Pit-FR	908.1 (587.7, 1403.2)	1258.6 (720.3, 2199.3)	1.39	522 (0.16)
Non pit-FR	295 (164.6, 528.7)	250.8 (155.8, 403.6)	0.85	−29 (0.56)
Restricted to pit users[a]				
Pre-intervention (n = 5)				
Pit-FR	1172.5 (495.4, 2775.2)	5264.3 (2270.3, 12,207)	4.49	6413 (0.06)
Non pit-FR	207.7 (56.9, 758.1)	193.9 (89.9, 418)	0.93	−76 (0.63)
Post-intervention (n = 7)				
Pit-FR	856.4 (467.4, 1569.1)	1689 (872.3, 3270.2)	1.97	1195 (0.03)
Non pit-FR	298.1 (132.9, 668.7)	317.6 (183.5, 549.8)	1.07	−38 (0.94)

ΣPit FR = Sum(TDCIPP, EH-TBB, BEH-TEBP, TPHP).
Σnon-pit FR = Sum(TCEP, TCIPP, BDE17, BDE28/33, BDE47, BDE66, BDE100, BDE99, BDE85/155, BDE154, BDE153, BDE138, BDE183, BDE209).
[a] Restricted to participants who reported using the foam pit that day during practice.

time, they may experience repeated high exposures during practice in addition to exposure in other microenvironments (home, school, etc.). Coaches and trainers can spend 40 h a week or more in the gymnastics training environment. Gymnastics coaches have been found to have elevated exposures to FRs during a work shift, with notably higher exposures when cleaning the foam pit (Ceballos et al., 2018; Broadwater et al., 2017). Our findings also have implications for other recreational facilities that utilize foam pits such as trampoline parks and climbing gyms that are used widely by children and teens, and may result in elevated exposures for frequent users and staff.

5. Conclusion

This is the first study to conduct flammability testing of foam cubes and mock foam pits, facilitate a fire inspection to replace the foam pit in a partner gym using foam free of additive FR, and quantify the change in gymnast FR exposure from this intervention. The interdisciplinary and engaged approaches of our study are important strengths, as is the use of hand-wipe samples as a non-invasive measure of gymnast exposure, and our ability to consider training in the foam pit as a risk factor for increased exposure during practice.

The FR-treated cubes had similar heat release rates to the non-FR treated cubes, required a 11 cm larger flame size applied for 6 s longer to ignite, and took 4 min longer to reach peak flame height. Based on our data and the presence of other fire safety measures, the local fire and building departments approved replacement of the foam pit with foam free of additive FR. We observed a 5-fold decline in the median mass of pit-FRs that accumulated on hands during practice among gymnasts who used the foam pit ($p = 0.02$), indicating that replacing the foam in a pit using FR-free foam can reduce gymnast exposure to FRs during practice. Future research should investigate the contribution of other FR sources in the gym such as the foam of landing mats as well as the effectiveness of handwashing and other exposure reduction strategies.

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Appendix A. Supplementary data

Supplementary Material (Figs. S1–S4, Tables S1–S5, Gymnastics Foam Pit Guidance and Checklist, and the Flammability Testing Letter Report) are available free of charge via the Internet. Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.01.084.

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