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Original Article

일부 화재현장에서 소방공무원의 직무별 다핵방향족탄화수소 및 휘발성유기화합물 노출평가

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Firefighters' Exposures to Polynuclear Aromatic Hydrocarbons and Volatile Organic Compounds by Tasks in Some Fire Scenes in Korea

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ABSTRACT

Objectives: Firefighters are known to be exposed to a variety of toxic substances, but little information is available on the exposure profile of firefighting activities. The aims of this study were to conduct exposure monitoring of toxic chemicals at fire scenes, to compare the concentrations of respective chemicals among firefighting tasks, and to assess the main factors influencing the concentrations of chemicals.

Methods: Researchers performed sampling at firefighting scenes during four weeks in 2013. At the scene, we collected samples based on firefighters' own activities and examined the situation and scale of the accident. Collected samples were classified into three categories, including fire extinguishing and overhaul, and were analyzed in the laboratory according to respective analysis methods.

Results: A total of fourteen fire activity events were surveyed: five fire extinguishing, six overhaul, and three fire investigations. Although no substance exceeded the ACGIH TLV, PAHs were detected in every sample. Naphthalene ranged from 0.24 to 279.13 mg/m^3 (median 49.6 mg/m^3) and benzo(a)pyrene was detected in one overhaul case at 10.85 $\mu g/m^3$. Benzene (0.01−12.2 ppm) was detected in every task and exceeded the ACGIH TLV. No significant difference in concentrations between tasks was shown.

Conclusions: These results indicate that all firefighting tasks generated various hazardous combustion products, including possible carcinogens.

Key words: BTEX, firefighters' exposures, firefighting activity, overhaul, PAHs

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목적: 소방관들은 각종 화재현장에서 다양한 유해화학물질에 노출된다고 알려져 왔다. 하지만, 이러한 소방활동이 이루어지는 동안 유해화학물질에 대한 노출이 어떤 형태로 되는 지, 노출되는 농도는 어느 정도인지 등에 대한 구체적인 연구나 조사는 거의 전무하다시피 한 상황이다. 따라서 이 연구의 목적은 첫째, 화재현장에서 소방관들이 개인적으로 노출되는 유해화학물질을 정성적, 정량적으로 모니터링하고 둘째, 각 화학물질의 농도가 소방업무와 어떠한 연관성이 있는 지 비교함과 동시에, 마지막으로 화학물질의 농도에 영향을 미치는 주요한 인자가 무엇인지에 대해서 평가하고자 하였다.

방법: 2013년 1월에서 4월까지의 기간 중 임의로 4주를 정하여 어느 화재현장을 대상으로 시료채취를 수행했고 이 때 소방관들의 직무나 화재현장의 특성, 즉 상황이나 규모 등을 함께 기록하였다. 취합된 시료는 세 가지 직무, 즉 화재진압, 오버홀 및 화재조사 등을 기준으로 분류되어 분석실로 보내어졌고 각 화학물질에 적합한 방법으로 분석되었다.

결과: 총 14건의 소방활동, 즉 화재진압 5건, 오버홀 6건, 화재조사 3건이 조사대상이었다. 채취된 모든 시료에서 벤젠을 제외하고 ACGIH-TLV를 초과한 화학물질은 없었지만, 발암물질인 PAHs의 경우는 모든 시료에서 한 종류 이상이 검출되었다. 이 중 나프탈렌은 0.24~279.13 mg/m^3 (중위값 49.6 mg/m^3)의 범위로 검출되었고, 벤조피렌은 한 건의 오버홀 직무에서 10.85 $\mu g/m^3$가 검출되었다. 벤젠(0.01~12.2 ppm)은 모든 직무에서 검출되었으며 한 개의 시료에서 ACGIH-TLV를 초과하기도 했으나 직무간 농도를 비교했을 때에 유의한 차이는 없었다.

결론: 이상의 결과는 여러 가지 한계가 있기는 하지만, 소방활동을 수행할 때 낮은 농도에 불과할지라도 발암물질을 포함하여 인체에 유해한 영향을 줄 수 있는 연소생성물이 발생한다는 것을 보여주고 있다. 향후, 소방업무를 수행하는 사람들이 직무를 수행할 때 노출되는 유해화학물질에 대한 보다 폭넓은 연구가 수행되어 이들의 건강을 보호하기 위한 명확한 근거 자료로써 활용할 수 있어야겠다.

주제어: BTEX, 소방관노출, 화재진압활동, 오버홀, PAHs

I. Introduction

Firefighters are heavily exposed to various adverse factors such as physical, psychological, chemical, and biological hazards during their occupational activities including emergency rescue, first aid, overhaul, and fire extinguishing. Recently, there has been increasingly concerned over the health hazards to firefighters because the use of new construction materials may release harmful gases with high toxicity (Jung, 2008). Firefighters are potentially exposed to wide range of chemicals such as polynuclear aromatic hydrocarbons (PAHs), benzene, formaldehyde, 1, 3-butadiene, xylene (Brandt-Rauf et al., 1988; Bolstad-Johnson et al., 2000). Some studies found that these exposures have increased cancer among firefighters. In a recent meta-analysis of 32 studies, multiple myeloma, non-Hodgkin's lymphoma, prostate cancer, and testicular cancer are related to firefighting activities. And also, skin, brain, anal, oral, pharyngeal, stomach and colon cancer, as well as malignant melanoma and leukemia, may be related to firefighting activities (LeMasters et al., 2008). The International Agency for Research on Cancer (IARC) has conducted meta-analyses of cancer among firefighters (IARC, 2010). They found that the rates of testicular cancer, prostate cancer, and non-Hodgkin's lymphoma were significantly increased in firefighters, and has classified firefighters as possibly carcinogenic to humans (Group 2B). Recent cohort studies have demonstrated that firefighters' exposures to PAHs and asbestos are related to an increased risk of prostate cancer, skin cancer, and lung cancer (Pukkala et al., 2008).

There have been some studies of exposure assessment to firefighters. Foreign studies have focused on exposures of firefighters in various scenarios, such as forest fires (Reisen & Brown, 2009; Miranda et al., 2012) and large building fires (Bolstad-Johnson et al., 2000). Nearly all fires will produce carcinogenic volatile organic compounds (VOCs) such as benzene and PAHs. Exposures to PAHs and benzene during overhaul were reported that PAHs concentrations exceeded the National Institute for Occupational Safety and Health Recommended Exposure Limits (NIOSH RELs), 0.1mg/m^3 and benzene exceeded the NIOSH Short-Term Exposure Limits (STELs), 1 ppm (Bolstad-Johnson et al., 2000). Another study showed that the concentrations for all individual PAHs were very low and among the 17 PAHs, only naphthalene and acenaphthylene were generally detectable (Bexter et al., 2014). Oliveira et al. (2016) found that firefighters' personal exposures to PAHs at Portuguese fire stations were well below the occupational exposure limits, however, there were significant positive correlations for firefighters between occupational exposure to PAHs and their metabolite levels. Fent et al. (2014) found that significantly elevated post-exposure breath concentrations of benzene compared with pre-exposure for firefighting activities. And also, they found that post-exposure levels of PAHs were significantly elevated compared with pre-exposure levels.

In Korea, the number of firefighters has been increased since 2003, and reached 44,121 persons in 2016. Yong et al. (2008) analyzed causes of death in the line of duty among firefighters over a 16-year period (1993 ~ 2008) in Korea: 87 of 189 (46%) deaths were caused by internal diseases, followed by vehicle accidents (24%), fire extinguishing (13%), and safety accidents (8%). Of the firefighters who died from internal diseases, 63% had brain cardiovascular disease and 30% had cancer. Cancer may be caused by carcinogenic substances such as benzene, benzo(a)pyrene, asbestos, and formaldehyde (Kim, 2008).. Direct causes of brain cardiovascular disease for firefighters include excessive physical activity, high temperatures, emotional stress, and inhalation of harmful gases present in fire and smoke (Han & Linton, 2008). However, few studies have been performed about exposure to toxic chemicals or gases, which may be very harmful to firefighters' safety and health.

Therefore, the objectives of this study were summarized in three points. At first, we conduct the exposure monitoring of toxic chemicals at eight scenes of fire in Korea, especially focused on PAHs and VOCs which are recognized as carcinogenic. Secondly, we compare the individual chemical's concentration among firefighting tasks: fire extinguishing, overhaul, and fire investigation. Finally, we assess the main factor influencing the concentrations of toxic chemicals.

II. Materials and Methods

1. Subjects

This study was conducted on fire scenes attended by the K fire station, which had the most mobilizations in Seoul in 2011. A K fire station attended 362 fire accidents, making it the busiest of the 22 fire stations administered by the Seoul Metropolitan Fire Headquarters or any other stations in Korea. The jurisdiction of K station includes dense residential areas, large-scale high-rise buildings, and cultural facilities at a high risk for accidents.

During any four weeks in 2013 (January 21~ February 15), researchers were on standby with firefighters and accompanied them on the first fire engine mobilized to the scene. Before arrival at a scene, sampling media were preloaded. At the scene, we removed filter plugs, broke sampling tubes, and examined the situation and scale of the accident. Simple smoke generation and small-scale fire accidents were excluded from research samples because there was insufficient time for sampling. Collected samples were classified into three categories such as fire extinguishing, overhaul, and fire investigation task, based on firefighters' opinions directly at the scene according to the conditions of live fire scenes. Fire extinguishing is defined as general extinguishing activities and prevention of fire spreading, overhaul as finding and extinguishing any remaining flames or charcoals inside the walls, ceilings, and floors after fire suppression, and fire investigation as identifying the cause of fire and estimating damage through data collection.

2. Sampling and Analytical Methods

We have monitored the personal exposures to firefighters on the target substances during their various tasks. The firefighters wearing the sampling equipment did not directly perform firefighting activities, but instead shadowed working firefighters or positioned themselves in rooms during firefighting activities. Considering the occupational requirement for vigorous activities and large movements at fire scenes, pumps were placed inside the bag to minimize limiting firefighter's activity and the tubes were put outside of the bag within the breathing zone of the firefighter. Personal breathing zone samples were collected for firefighters to characterize their exposure levels. Samples were from eight fire scenes near the K fire station in Seoul during the study period (January 21~ February 15, 2013). There were various locations, for example, a laundry, an outlet store, a temporary building, an underground parking lot, a sauna in a public bath, an apartment, a printing house, and a restaurant congested building. All the air sampling pumps were fully charged and calibrated every day. Sampling time was generally ranged from 10 to 116 minutes.

Firefighters' personal exposure samples were collected by each activity and each sample was recorded with its location, sampling time, and sampling duration. All the samples had been placed in their respective prelabeled bags and stored in a icebox before being moved to the laboratory.

1) Polynuclear Aromatic Hydrocarbons (PAHs)

PAH samples were collected using a high-volume flow rate pump (GilAir-5, Gilian, St. Peterberg, FL, USA) equipped with a Polytetrafluoroethylene (PTFE) filter (2.0 μm, 37 mm, Gelman Zefluor, Milipore, USA) and connected to a XAD-2 (150 mg/75 mg, SKC, Eighty Four, PA, USA) using PVC tubing. The pumps were calibrated to 2.0 L/min. The filter and XAD-2 were wrapped in aluminum foil to protect against light exposure. Samples were shipped to the laboratory in an insulated container with bagged refrigerant after collection. Samples were analyzed according to NIOSH Manual of Analytical Method (NMAM) 5515 using gas chromatography-mass spectrometry (GC-MS). Analytical substances were as follows: naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo(a)anthrancene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, indeno(1,2,3-c,d)pyrene, dibenzo(a,h) anthrancene, benzo(g,h,l)perylene.

2) Volatile Organic Compounds (VOCs)

Analytical substances out of VOCs were benzene, toluene, ethylbenzene, and m,p,o-xylene (BTEX). BTEX samples were collected using a low-volume flow rate pump (LFS113, Gillian, USA) equipped with coconut charcoal tubes (100mg/50mg, SKC, Eighty Four, PA, USA). Pumps were calibrated to 0.2 L/min. Samples were also shipped to the laboratory in an insulated container with bagged refrigerant after collection. Samples were analyzed according to NMAM 1501 using GC-FID.

3) Quality Control

We used both laboratory and field blanks for performing quality control to assess the accuracy and precision of our analyses. For laboratory blanks, reproducibility of the analytical instrument and recovery of spiked sample were evaluated. Limit of detection (LOD) was calculated by multiplying by 3.14 standard deviations of seven replicates of the lowest standard solution. Samples below the LOD were classified as ND (not detected). For field blanks, three blank samples in each site were moved, sampled and analyzed on the same circumstances like other gaseous samples. Then, average values of field blanks were subtracted from ones of gaseous samples by site.

3. Statistical Analysis

The Mann-Whitney U test was performed to examine differences in exposure levels between firefighting activities, especially for fire extinguishing and overhaul. A multiple regression analysis was also performed to assess any correlations among target substances' concentrations (independent variable) and firefighting tasks, confinement states, burnt area sizes, numbers of people mobilized, work time, numbers of equipment mobilized, amounts of damage, and building materials (dependent variables). Statistical analysis was performed using SPSS statistical software (Version 21.0, IBM, Armonk, NY, USA).

III. Results

Table 1 lists the related information on each fire scene. Eight fire scenes actually included fire extinguishing, overhaul, and fire investigation activities. Fourteen samples were collected during the five fire extinguishing, six overhaul, and three fire investigation activities. Two out of eight locations were confined spaces including an apartment and a sauna in public bath. Each location had some kinds of combustibles, for example, clothing, steel reinforcement, household items, etc.

The situations during firefighting activities differed from each location, so there were limitations in measuring the series of each fire activity in all samples. Also, average concentrations of target substances were heavily influenced by some extreme values, therefore we used median instead of average values for accuracy.

1) Polynuclear Aromatic Hydrocarbons (PAHs)

Of the sixteen PAHs, only naphthalene was

Table 1. Background and sampling information on the firefighting areas in this study

Location	Characteristics of each fire scene			Firefighting activity*			Sampling information	
	Confinement state	Combustibles	Size (m^3)	Extinguishing	Overhaul	Investi-gation	Number	Time (min)
Laundry	No	Laundry room fire to structure, Electronic Vapor Recovery System, Clothing	244.4	○	○	×	2	19–20
Outlet store	No	Clothing, Fabric, Upholstery materials, Steel reinforcement	599.9	○	○	×	2	20–32
Apartment	Yes	Pipe insulation film materials, Household ceiling spaces, Textiles	4.0	×	○	×	1	10
Temporary Building	No	Refrigerator, TV, Furniture, Household items, Steel reinforcement	150.0	○	○	×	2	26–29
Printing house	No	Boxes, Plastic, Paper, Printing, Machine	1,243.0	×	×	○	1	60
Underground parking lot	No	Plastic, Paper, Car	–†	○	○	×	2	12–33
Sauna in public bath	Yes	Wood, Pipe, Radiator, Steel reinforcement	100,496.7	○	○	○	3	29–54
Restaurant congested buildings	No	Contents of kitchen, Concrete structure, Steel reinforcement	3,896.0	×	×	○	1	116

*○, samples acquired; ×, no samples acquired
†No data

detected in all the samples from both fire extinguishing and overhaul activities. Other compounds identified during fire extinguishing activity included benzo(a)anthrancene, chrysene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo(a) anthrancene, chrysene, indeno(1,2,3-c,d)pyrene, and benzo(g,h,l)perylene. And, during overhaul activity, other compounds were also detected such as acenaphthylene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo(a)anthrancene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a) pyrene, indeno(1,2,3-c,d)pyrene dibenzo(a,h)anthrancene, and benzo(g,h,l)perylene. Compounds detected during fire investigation activity included naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, chrysene, indeno(1,2,3-c,d)pyrene dibenzo(a,h)anthrancene, and benzo(g,h,l)perylene.

Table 2 shows major PAHs concentrations according to tasks. All of the PAHs concentrations in this study were much below their occupational exposure limits. However, one or more PAHs were found at all sites. Especially, naphthalene and chrysene were generally detected, which were possibly carcinogenic to humans (Group 2B) based on the IARC. And also, benzo(a)pyrene that was carcinogenic to humans (Group 1), was detected during overhaul at one site. Maximum concentration of each PAH was mostly at sauna in a public bath, and many kinds of PAHs were generally detected at apartment, a sauna in a public bath, and an outlet store.

2) Volatile Organic Compounds (VOCs)

Benzene, toluene, ethylbenzene, and m,p,o-xylene

Table 2. PAHs Concentrations according to firefighting tasks

PAHs	Fire extinguishing (N=5)		Overhaul (N=6)		Investigation (N=3)	
	Median (μg/m^3)	Range (μg/m^3)	Median (μg/m^3)	Range (μg/m^3)	Median (μg/m^3)	Range (μg/m^3)
Naphthalene	93.95	6.22-2,082.60	49.59	0.24-279.13	320.22	17.43-623.01
Acenaphthylene	24.79	13.32-120.10	10.40	1.11-28.01	33.42†	-
Acenaphthene	7.28†	-	ND*	-	2.81†	-
Fluorene	2.59	0.28-24.87	2.05	0.17-5.46	6.10†	-
Phenanthrene	1.09	0.35-17.29	22.07	11.06-43.46	2.18	0.92-3.44
Anthracene	2.30	1.69-2.92	6.73	1.38-12.09	0.97†	-
Fluoranthene	0.63	0.45-3.27	16.94	4.99-44.14	0.78†	-
Pyrene	0.44	0.22-1.97	11.34	0.67-34.89	0.27	0.13-0.4
Benzo(a)anthrancene	1.57†	-	6.25	2.40-10.09	ND*	-
Chrysene	0.68	0.36-1.38	6.31	1.58-17.37	0.35	0.11-0.59
Benzo(b)fluoranthene	ND*	-	13.21	4.65-26.91	ND*	-
Benzo(k)fluoranthene	ND*	-	10.85†	-	ND*	-
Benzo(a)pyrene	ND*	-	15.13†	-	ND*	-
Indeno(1,2,3-c,d)pyrene	0.48†	-	12.88	2.38-12.94	0.05†	-
Dibenzo(a,h)anthrancene	ND*	-	2.06	0.81-3.82	0.29†	-
Benzo(g,h,l)perylene	2.22	1.02-3.42	7.53	3.27-12.35	0.84	0.49-1.2

* ND, Not Detected - LOD were as follows; Naphthalene, 0.0448 μg/m^3; Acenaphthylene, 0.0912μg/m^3; Acenaphthene, 0.0400 μg/m^3; Fluorene, 0.0075 μg/m^3; Phenanthrene, 0.0032 μg/m^3; Anthracene, 0.0031 μg/m^3; Fluoranthene, 0.0082 μg/m^3; Pyrene, 0.0053 μg/m^3; Benzo(a)anthrancene, 0.0054 μg/m^3; Chrysene, 0.0041 μg/m^3; Benzo(b)fluoranthene, 0.0041 μg/m^3; Benzo(k) fluoranthene, 0.0053 μg/m^3; Benzo(a)pyrene, 0.0049 μg/m^3; Indeno(1,2,3-c,d)pyrene, 0.0049 μg/m^3; Dibenzo(a,h)anthrancene, 0.0048 μg/m^3; benzo(g,h,l)perylene, 0.0048 μg/m^3

†Detected only once

Table 3. VOCs Concentrations according to firefighting tasks

VOCs†	Fire extinguishing (N=5)		Overhaul (N=6)		Investigation (N=3)	
	Median (ppm)	Range (ppm)	Median (ppm)	Range (ppm)	Median (ppm)	Range (ppm)
Benzene	0.681	0.05-12.2	0.177	0.001-4.66	0.271	0.042-1.10
Toluene	0.107	0.001-2.09	0.396	0.02-0.771	0.085	0.052-0.11
Ethylbenzene	0.21	0.1-0.32	0.091	0.006-0.18	0.021*	-
m,p-Xylene	0.245*	-	0.057*	-	0.071*	-
o-Xylene	0.064	0.05-0.1	0.036*	-	0.015*	-

* Detected only once

† LODs were as follows; Benzene 0.002119 ppm; Toluene 0.000379 ppm; Ethylbenzene 0.001585 ppm; m,p-Xylene 0.00113 ppm, o-Xylene 0.000505 ppm

(BTEX) were analyzed. Benzene was the major substance to which firefighters were exposed, and it was detected in all of the samples during all three tasks. Also, benzene was present at relatively higher concentrations than any other substances such as toluene, ethylbenzene, and xylene. Toluene was detected in three of the five fire extinguishing activities, two of the six overhaul activities, and two of the three investigation activities. Ethylbenzene was detected in two fire extinguishing, two overhaul, and one fire investigation.

Table 3 shows BTEX concentrations according to tasks. Most of the BTEX concentrations in this study were much below their occupational exposure limits. Benzene concentrations during firefighting activities were somewhat higher than NIOSH REL (0.1 ppm) and especially its concentration during fire extinguishing was exceeded half of Permissible Exposure Limit (PEL), 1 ppm. All kinds of BTEX were detected during fire extinguishing at sauna in a public bath and during investigation at printing house.

The Mann-Whitney U test analysis was conducted with two groups to compare the concentration levels of frequently detected substances including naphthalene, chrysene, benzene, and toluene between fire extinguishing and overhaul tasks (Table 4). However, it showed no significant difference ($p>0.05$).

A multiple regression analysis was conducted to identify the correlation between concentration levels and probably influencing factors such as tasks, confinement states, numbers of firefighters dispatched, work time, numbers of mobilized equipment, property damages, and building

Table 4. Comparison of major detected substances between the tasks

Substance	Task	N	Median	Range	p-value
Naphthalene	fire extinguishing	5	93.95	6.22-2,082.68	0.548
	overhaul	6	49.59	0.24-279.13	
Chrysene	fire extinguishing	5	0.68	0.36-1.38	0.421
	overhaul	6	6.31	1.58-17.37	
Benzene	fire extinguishing	5	0.681	0.046-12.199	0.421
	overhaul	6	0.210	0.027-4.66	
Toluene	fire extinguishing	5	0.107	0.001-2.094	0.548
	overhaul	6	0.396	0.020-0.771	

Table 5. Results of multiple regression analysis between concentration levels and significantly influencing factors

Substance	Variable	β	Adjusted R^2	p-value
Naphthalene	Confinement state	747.85	0.191	0.009†
Chrysene		6.349	-0.020	0.011*
Benzene		5.086	0.415	0.004†
Toluene		0.74	0.201	0.016*

* $p<0.05$; † $p<0.01$

materials as independent variables. As a result, only confinement state had a significant relationship with concentration levels of major detected substances (Table 5). Other factors including tasks, numbers of people dispatched, work time, numbers of mobilized equipment, property damages, and building structures were not significant, so they were not shown in the table.

Ⅳ. Discussions

In this study, we investigated the chemical concentrations while conducting three kinds of tasks at live eight fire scenes. The results demonstrated that the firefighters were exposed to some carcinogenic substances such as benzene and PAHs including naphthalene. We generally compared air concentrations of hazardous chemicals in fire scenes with 8-hr weighted average although sampling time was relatively short, because we wanted to predict the long-term effects to firefighters in case of exposure to the same levels. Although their levels were mostly low, the chemicals found in this study have the potential to cause harmful health effects to firefighters.

We showed that PAHs such as naphthalene and chrysene were found at most fire scenes. Naphthalene, which the IARC categorizes as Group 2B (possible carcinogenic to humans), was present at higher concentrations than previous studies in case of fire extinguishing and overhaul activities. In this study, the highest concentration of naphthalene in fire extinguishing activity was 2,082.6 μg/m^3 detected at a sauna in a public bath, however Kim (2007) suggested 1,106 μg/m^3. This fire scene was located in the basement, which was a confined place filled with heavy smoke. The higher concentration may be affected by poor ventilation and underground space. However, the concentration level did not exceed the ACGIH (American Conference of Governmental Industrial Hygienists) Threshold Limit Value-Time Weighted Average (TLV-TWA) value of 50,000 μg/m^3. Chrysene, which is also Group 2B categorized by IARC, was detected during three firefighting activities at all fire scenes, but its level was generally very low. Previous studies showed lower concentration of chrysene in fire extinguishing and overhaul activities. Concentrations of benzo(a)pyrene, which is a well-known carcinogen that causes lung, stomach, and skin cancer (Sadikovic & Rodenhiser, 2009), was ranged from 1 to 50 μg/m^3 in some studies. Kim (2007) and Jakovic et al. (1991) showed 48.0 μg/m^3 as the highest levels detected in fire extinguishing and Bolstad-Johnson et al. (2000) showed 50.0 μg/m^3 in overhaul. In this study, benzo(a)pyrene was detected at concentration of 10.85 μg/m^3 during only overhaul task at a sauna in a public bath. This level was lower than previous studies and also did not exceed the occupational exposure limit.

Benzene, which is known to cause leukemia, is categorized as Group 1 carcinogen by IARC, was detected in all samples collected during fire extinguishing, overhaul and fire investigation tasks except one overhaul task in this study. And this was detected at relatively high concentrations compared to other chemicals such as toluene, ethylbenzene, and xylene. Previous studies including Austin et al. (2001) and Jakovic et al. (1991) have reported that benzene concentrations during firefighting activity can exceed the ACGIH TLV of 0.5 ppm. In this study, a concentration of 12.2 ppm was detected in the sample from one fire extinguishing activity: this level significantly exceeds the ACGIH TLV-TWA value. It was assumed that high concentration of benzene may have occurred because of a confined underground sauna with poor ventilation. Benzene levels also exceeded the ACGIH TLV-TWA concentration in two cases of overhaul, and one case of fire investigation. Toluene was detected at all firefighting activities, and its level was somewhat similar with those of previous studies such as Brandt-Rauf et al. (1988). However, its concentration was much lower than occupational exposure limit.

Several previous studies have been performed during fire extinguishing or overhaul tasks, but few studies have included fire investigation. We have sampled at fire investigation activity and found that naphthalene was present at higher concentration (17.43~623.01 $\mu g/m^3$). Some other harmful materials including chrysene, benzene and toluene were present, however they were relatively very low. This result showed that firefighters could be exposed to very critical chemical components in even safer investigation activity.

The Mann-Whitney U test analysis (a non-parametric testing method) was used to compare concentration levels between fire extinguishing and overhaul task, but no significant differences were observed among the two groups ($p>0.05$). Despite these results, there were risks exposed to harmful chemicals at fire scenes because some poisonous materials, for example naphthalene, showed a higher concentration during firefighting rather than overhaul activity. And also, multiple regression analysis was used to identify any correlation between airborne exposure levels and influencing factors such as tasks, confinement states, numbers of firefighters dispatched, work time, numbers of mobilized equipment, property damages, and building structures as independent variables. We found that a statistically positive significant correlation between concentrations of mostly detected chemicals such as naphthalene, chrysene, benzene, toluene and confinement states ($p<0.05$; $p<0.01$). It means that environmental factors such as poor ventilation can be a very important one from a viewpoint of firefighters' safety.

All the fire scenes in this study were located within a building. In modern buildings, the majority of components such as carpets, wallpapers, furniture, contain polyethylene and PVC has been known to produce a variety of toxic chemicals including carcinogens when burned. Firefighters entering a site to rescue victims (the highest priority among fire extinguishing activities), and conducting fire extinguishing operations near a fire, are generally required to wear a self-contained breathing apparatus. However, supporting personnel, which are the persons to drive, communicate, supervise, and maintain a distance using fire hoses, do not often wear any air respirators. Even firefighters may enter a scene without wearing air respirators due to communication problems or physical exhaustion or overheat during overhaul and fire investigation. This means that lots of firefighters may be directly exposed to harmful substances with adverse effects to their health. Although the concentrations for PAHs and BTEX were very low, there could be potential simultaneous exposure to multiple chemicals even in small quantities in combination with other exposure such as high ultrafine particle.

Exposure to toxic gases during all the firefighting activities including fire extinguishing, overhaul, and fire investigation tasks, should be evaluated and well prepared in terms of health effects. Many toxic gases are produced during a fire and remain in the atmosphere. The environment is not as hot or smoky during overhaul or fire investigation task, but based on this study, harmful substances still in existence as products of combustion from small fires or smoldering material. Therefore, our results showed that self-contained breathing apparatus should be required to firefighters during fire extinguishing, overhaul, and fire investigation tasks. Also, we found that environmental factors for the fire site, for example, the confinement state, may have significant influences on firefighters' chemical exposures.

There are some limitations in this study. At first, because of different characteristics in each fire scene such as a variety of the type and amount of materials, it was difficult to identify trends within each task. Previous studies have also reported difficulties in estimating the type and amount of substance. Actual fire scenes differ so greatly that direct comparison may be challenging. Secondly, fire sites included a mix of hazardous materials that were not easily characterized. There are inadequate published documents for combination of contaminants, however, adverse health effects may occur from exposure to a mixture of products of combustion although concentrations of individual components are very low. Thirdly, this study has basic difficulties to perform the measurement for hazardous materials in fire sites. The most important thing in fire scenes is to extinguish the fire as well as firefighters' safety. And it is also too urgent to monitor samples at any time. This is why we cannot measure enough samples for this study. Finally, evaluation of exposure at fire scenes should not be limited to one or two projects; work environments of firefighters should be regularly measured to create a database from collected data.

V. Conclusion

We performed this study to identify hazardous substances during fire extinguishing, overhaul, and fire investigation activities. Firefighters were exposed to some carcinogenic chemicals including benzene and naphthalene. Their concentrations did not exceed the occupational exposure limits except benzene, however, major detected substances may cause adverse health effect to firefighters during firefighting activities. Although the environment during overhaul and fire investigation tasks may not appear as dangerous as during fire extinguishing tasks, it may still contain hazardous combustion products. Therefore, a self-contained breathing apparatus must be worn to minimize exposure to hazardous substances at every fire scene. Although the fires that occurred in this study period were in different locations and it was not possible to repeat the same fire scenes due to the nature of fire accidents, these results suggest that the future direction of research in the field of occupational health for firefighters working in fire scenes that are difficult to access. They may also be used to inform research about health hazards to firefighters, and may provide a basis for assessing exposure and improving the work environments of firefighters. Most of all, it can be expected to provide actual data for the firefighters' health effects from toxic gases in fire scenes although the practical limitations and few references about firefighters' exposure assessments.

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