fire

Article

Evaluation of Air Quality inside Self-Contained Breathing Apparatus Used by Firefighters

Soo Jin Kim [1,2] and Seunghon Ham [3,*]

[1] Department of Epidemiology, Graduated School of Public Health, Seoul National University, Seoul 03312, Republic of Korea; kdamian0@snu.ac.kr
[2] Seoul Metropolitan Fire & Disaster Headquarters, Seoul 03312, Republic of Korea
[3] Department of Occupational and Environmental Medicine, Gil Medical Center, Gachon University College of Medicine, Incheon 21565, Republic of Korea
* Correspondence: shham@gachon.ac.kr; Tel.: +82-32-458-2634

Abstract: (1) Background: When a fire breaks out, combustibles are burned and toxic substances such as carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAH), benzene, and hydrogen cyanide are produced. The purpose of this study is to evaluate the air quality inside self-contained breathing apparatus (SCBA) by comparing it to that in the environment where the SCBA charger is installed. (2) Methods: The design of this study was a simulation-based case-control experiment study, and the experiment was conducted at two fire stations located on land and on water. When charging the SCBA, it was differentiated according to the presence or absence of exposure to harmful substances and the degree of exposure. The air quality inside the SCBA in the charging room installed in the fire station garages located on land and in the water, which were not completely isolated from harmful substances, was evaluated. CO, carbon dioxide (CO_2), water, and oil mist were measured and analyzed to determine the air quality inside the SCBA. (3) Results: In the case of land firefighting stations, the mean CO among the SCBA internal air quality items was 20 times higher than the outside the SCBA, and higher than the safe range in the group with the highest exposure at the sites of firefighting buildings completely isolated from hazardous substances. The CO levels of all items of water were analyzed to be higher than the safe range in the floating fire station. (4) Conclusions: It was confirmed that the installation environment of an SCBA charging room can affect the safety of the charged internal air quality components. The results of this study can be actively used for the operation and management of SCBA charging room environments when building firefighting buildings in the future for the hygiene, safety, and health of firefighters.

Keywords: firefighter; self-contained breathing apparatus (SCBA); air quality; SCBA charging environment; CO; water

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1. Introduction

When a fire breaks out, toxic substances and carcinogens such as carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAH), volatile organic compounds (VOC), benzene, hydrogen cyanide (HCN), benzo[a]pyrene, hydrogen fluoride and per- and polyfluoroalkyl substance (PFAS) are generated at the fire scene through the combustion process [1–14]. Firefighters face various dangers at a fire scene, such as collapse, explosion, and isolation. Because toxic substances generated at the fire scene contain many components that can cause cancer, firefighters must wear personal protective equipment (PPE) before entering [15–18]. In particular, self-contained breathing apparatus (SCBA) is one of the most important pieces of PPE and supplies external breathing air for the safety of firefighters who extinguish the fire and rescue people trapped in fires [19–22]. SCBA is a type of PPE used by firefighters in extreme working environments, so proper use and management is essential to ensure proper functioning. Because SCBA is made of aluminum owing to its low weight and pressure resistance, when exposed to moisture, aluminum hydroxide powder is generated leading to internal corrosion [23]. In the past, this phenomenon occurred in the Republic of Korea, where internal air component analysis of SCBA was conducted and managed by a specialized testing agency at least once every six months [24]. In the Republic of Korea, firefighting equipment laws and related regulations stipulate that the SCBA cylinder used by firefighters, the SCBA charging facility, and air quality must be analyzed inside SCBA. In particular, the requirements for the location of the charging room for the safe operation of SCBA chargers is stipulated in Article 10 of the Standards for Respiratory Protection Equipment Safety Management (National Fire Agency Notification No. 2019-24, 2019.2.22.) as follows: First, in order to prevent the inflow of polluted air, the structure must be partitioned separately from the surrounding facilities. Second, the ventilation system recommended by the manufacturer must be installed so that the indoor temperature is maintained at 5 °C~45 °C during air charging work, or the indoor air must be quickly exhausted. Third, electrical facilities must be installed such that the motor and various air-charger facilities are suitable for use [25]. SCBA's technical standards for the type approval and product inspection (National Fire Agency Notice No. 2022-27, 2022.12.1.) also stipulate details including the structure, testing, and pressure of the air chargers [26]. From the 2000s to the present, the issue of corrosion and foreign matter detection in respirators has continued in Korea; therefore, the management of respirators for the safety of firefighters is crucial. The safety of SCBA and other PPE used by firefighters worldwide is so vital that it is constantly being addressed [27]. Compared to overseas cases such as the United States, Korea stipulates the environmental conditions of the SCBA charging room in related laws, but it does not meet them, so environmental improvement is needed. In accordance with the Fire Equipment Act of Korea, SCBA is inspected twice a year for corrosion and foreign substances. However, the environment for filling SCBA has not been evaluated [24,25]. In addition, related laws and regulations stipulate an installation environment for SCBA charging facilities in fire-affected buildings; however, most fire stations do not meet this requirement. No study has been conducted on how the difference between SCBA installation and the operating environment in an actual fire station affects the air quality inside the SCBA, and the results have not been clarified.

Therefore, the purpose of this study was to evaluate the air quality inside the respirators used by firefighters compared to that in the installation environment of the fire station charging facility.

2. Materials and Methods

2.1. Study Setting

In the Republic of Korea, all conditions for SCBA charging facilities and environmental management are based on the firefighting equipment management work processing standard, which is a directive from the National Fire Agency (NFA). According to Annex 7 of the directive, the standards for the safety management of respiratory protection equipment, stipulate that the charging room should be structured separately from the surrounding facilities to prevent the inflow of contaminated air. It has 58 SCBA charging devices, including at 25 fire stations, fire academies, and 119 Special Rescue teams under the Seoul Fire and Disaster Headquarters. SCBA chargers were installed and operated by designating two safety centers (including response teams) for each fire station. The installation environments for the SCBA charging devices in the fire departments under the Seoul Fire and Disaster Headquarters were classified into five types. First, 33 charging devices were installed in the SCBA charging room. Second, 13 SCBA chargers were installed in a separate space. Third, seven locations were installed in warehouses. Fourth, only one was installed in another indoor training center. Lastly, four locations were installed in the fire station garage. The location in the fire station's garage is an environment where contaminants of harmful substances do not completely block the SCBA charging room. As such, the SCBA charging rooms installed and operated by the various fire departments or 119 Safety Centers did not meet all the respiratory protection equipment safety management standards stipulated by the law. One reason for this is the narrow area of fire station buildings in

Seoul, a large city. This study aimed to compare and evaluate the air quality components of respirators charged in the SCBA charging rooms of firefighting stations operating in accordance with safety management regulations for respiratory protective equipment and those of non-operating fire stations.

2.2. Experimental Setting

This experiment measured the air quality inside SCBA charged under different SCBA charging environments based on a simulation. The experiment was conducted at two fire stations located on land in a large city and two fire stations of a water rescue team located on the water. For the onshore fire station, we selected a location where the SCBA charging environment of the charging rooms was not completely or partially blocked from exposure to harmful substances. The fire department of the water rescue team conducted the experiment in a manner similar to the aforementioned experimental conditions. Guro Fire Station, an experimental site installed on land, selected one each of the response teams and the 119 Safety Centers. The SCBA charger installed by the response team is installed and operated in a space not separated by a screen inside the fire garage (case group). The Sindorim 119 Safety Center is inside a space divided into separate rooms composed of containers and a temporary building in the fire department. An SCBA charger was installed and operated as a control group. To ensure the success of the SCBA internal air quality evaluation experiment based on the difference in the SCBA charging environment, a preliminary experiment was conducted once at the same experimental site. Based on this result, the experiment was conducted with modifications after reviewing the experimental design, environment, and results. The experiment on land was conducted on Thursday, 6 May 2021, from 8:30 am to 1:00 pm, by the response team of the Guro Fire Station, and from 2:30 pm to 3:30 pm at the 119 Safety Center in Sindorim. On the day of the experiment, the weather was clear, the lowest temperature was 13 °C, and the highest temperature was 23 °C.

The 119 Special Rescue Services in water conducted experiments on water rescue teams in Yeouido and Banpo in Seoul. The water rescue team conducts water-based lifesaving and firefighting activities in case of a fire on a watercraft. Both operate on barges floating in the Han River 365 days a year and are characterized by a lot of water very close to the SCBA charging room. The Yeouido Water Rescue Team conducted the experiment on Friday, 20 August 2021 from 8:30 am to 1:00 pm, and the weather was clear, the waves were calm, and there was no wind. On Friday, September 6, from 8:30 a.m. to 1:30 p.m., the experiment was conducted at the Banpo Water Rescue Unit. It was sunny, but the river flowed fast due to the east wind at 4–6 m/s. In the control group, the experiment was conducted in the SBCA charging room inside the water rescue unit and was measured after blocking all the soot generated from the firefighting vessel. The firefighting equipment was operated close to the firefighting vessel and the SCBA charging room, and the experiment was conducted under conditions in which smoke and harmful substances were generated. In the SCBA charging room installed and operated at the floating fire station, the SCBA and SCUBA cylinders used in fire and water rescue scenes were used for the experiments. The SCBA for fire suppression and the SCUBA for water rescue are different. In the case of a ship fire, SCBA is used for fire suppression and in the case of a water accident, SCUBA is used for water.

2.3. Study Design and Subject

The design of this experimental study is a simulation-based case-control study. In an experiment conducted at a land fire station, the case group measured the internal air qual-ity of SCBA filled in a place where the room was not completely or partially blocked from soot and harmful substances. That is, the SCBA was charged while being exposed to harmful substances. The control group measured the air quality inside the SCBA in the SCBA charging room installed in a place completely blocked from soot and harmful substances at the fire station. In other words, they were charged while completely isolated from exposure to harmful substances and fumes. However, the control group was located near a road with traffic. In particular, the case group could be exposed to various harmful substances inside the fire station garage; therefore, the experimental group's conditions were divided into four groups and measured. Group 1 filled the SCBA cylinder to its usual level in the respirator charging space installed in the garage. Group 2 filled the SCBA cylinder only when firefighting vehicles with an engine level of Euro 6 were started. Group 3 filled the SCBA cylinder when firefighting vehicles with engine levels of Euro 5 and Euro 6 were started. Group 4 filled the SCBA cylinder in an environment in which all firefighting vehicles with engine levels of Euro 4, Euro 5, and Euro 6 were started. The air quality inside the SCBA was measured for each group (Table 1). Euro 4, 5, and 6 refer to the engine levels used in fire engines, and Euro 6 engines produce the lowest diesel emissions, while Euro 4 engines produce the highest. Therefore, differences in engine levels can affect the charge air quality in fully or partially unblocked SCBA charging rooms.

In an experiment conducted at a floating fire station, the case group measured the air quality inside the SCBA in an environment where smoke and harmful substances were generated by operating firefighting equipment in a place close to a firefighting vessel and an SCBA charging room. In particular, there are two types of SCBA for fire suppression and SCUBA for water rescue due to the nature of work in the water rescue team, and both were measured. In the control group, the air quality inside the SCBA/SCUBA was measured in an environment in which all soot generated in the firefighting vessel was blocked (Table 2).

The SCBA and SCUBA were measured three times in each environment to minimize bias in the experimental results owing to measurement errors. In addition, all the SCBA and SCUBA cylinders used in the experiment were used in actual firefighting, water rescue activities, and the work environment of the firefighters was reflected as much as possible (Table 3).

2.4. Experimental Scenario and Sampling Strategy

The experimental environment was created to be similar to the charging environment of SCBA at the fire stations, and the experiment was conducted considering the worst occupational working environment. The experimental scenarios and sampling strategies of the case group (Guro fire station and response team) conducted at the land fire station are as follows:

1. An exhaust reduction system (ERS) is a valuable strategy to mitigate pollutant exposure among firefighters and outdoor air pollution using the filtration ability of an ERS. After switching the ERS installed in the fire station to manual mode, all doors connected to the outside of the garage of the fire station were closed and the firefighting vehicle did not start and waited for 5 min. After the measuring equipment was located and operated, it was confirmed that the equipment was operating normally, and the particulate and gaseous matter were measured.
2. In Group 1, a single SCBA cylinder was charged in a basic environment, and after charging the SCBA cylinder, four air quality parameters were measured.
3. Group 2 started a firefighting vehicle with an engine level of Euro 6 for 15 min, charged three SCBA cylinders simultaneously in this environment, and then brought the cylinders outdoors. Four air quality parameters were measured for each of the three SCBA cylinders.
4. Group 3 only started firefighting vehicles with engine levels of Euro 5 and 6 for 15 min. In this environment, three SCBA cylinders were charged at the same time, and the cylinders were taken outdoors. Four air quality parameters were measured for each of the three SCBA cylinders.
5. Group 4 started all firefighting vehicles with Euro 4, 5, and 6 engine levels for 15 min, charged three SCBA cylinders simultaneously in this environment, and then, took the cylinders outdoors. Four air quality parameters were measured for each cylinder.

Table 1. Experimental environment outline at the onshore fire stations.

	Experiment Date	Location	Environment of SCBA Cylinder Charging Room	Number of Fire Engines in SCBA Cylinder Charging Room	Subject	Others
Case Group	6 May 2021.Fri. 08:10~13:00	Guro fire station response team	Installed and operated while exposed to smoke and harmful substances in the garage of the fire station	Total 20	SCBA for firefighting, 12 cylinders	
Control Group	6 May 2021.Fri. 14:30~15:30	Guro fire station Sindorim 119 Safety Center	SCBA charging room is completely blocked from garage fumes and harmful substances, near a traffic road	None	SCBA for firefighting, 3 cylinders	

Table 2. Experimental environment outline at the floating fire stations.

Experiment Date	Location	Environment Of SCBA Cylinder Charging Room	Subject	Others
20 August 2021 Fri. 08:10~13:00	Seoul 119 Special Rescue Services, Yeouido Water Rescue Team	SCBA and SCUBA charging chamber not fully or partially shielded from ship fumes and harmful substances	SCBA (firefighting 6 cylinders), SCUBA (water rescue, 6 cylinders)	
6 September 2021.Fri. 08:10~13:00	Seoul 119 Special Rescue Services, Banpo Water Rescue Team	SCUBA charging room completely blocked from ship fumes and harmful substances	SCBA (firefighting 6 cylinders), SCUBA (water rescue, 6 cylinders)	

Table 3. Overview of experiments conducted by SCBA group at the onshore fire station.

	Group 1	**Group 2**	**Group 3**	**Group 4**
Exposure condition	Measured at usual level Fire vehicle start (−) Pollutant (−)	Engine-level-Euro 6 fire truck startup (+) Pollutant (+)	Engine-level-Euro 5~6 fire truck startup (+) Pollutant (+)	All fire trucks started up (+): Engine-level-Euro 4~6 Pollutant (+)
Number of SCBA cylinder	3 set	3 set	3 set	3 set
SCBA Manufacturing company Country of manufacture	Sancheong Republic of Korea	Sancheong Republic of Korea	Sancheong Republic of Korea	Sancheong Republic of Korea

Exposure condition: If there is exposure due to sanitary conditions in the fire station garage, it is marked as (+), if there is no exposure, it is marked as (−); Number of SCBA cylinder: Number of SCBA cylinders used by group in this study; SCBA Manyfacturing company: Name of SCBA manufacturer; Country of manufacture: Refers to the country of the SCBA manufacturer.

The experimental scenario and sampling strategy of the control group (Guro fire station, Sindorim 119 Safety Center) conducted at the onshore fire station were as follows:

1. After confirming that the experimental equipment and the SCBA charging equipment were operating normally, the particulate matter and gaseous matter in the measurement environment were measured.
2. Three SCBA cylinders for fire suppression were filled in an environment blocked from harmful substances emitted when the ship and various types of firefighting equipment were started. Four air quality items in the SCBA cylinders were measured.
3. Three SCBA cylinders for water rescue were filled in an environment that was blocked from harmful substances discharged when starting ships and various firefighting equipment. Four air quality items in the SCBA cylinders were measured.
4. All ships in the water rescue team were started, the doors of the air charging room were opened, and three SCBA cylinders for fire suppression were filled in an environment that was not blocked from soot and harmful substances, and four air quality items were measured.
5. All ships in the water rescue team were started. The doors of the air charging room were opened to fill three SCBA cylinders for water rescue in an environment that was not blocked from soot and harmful substances, and four air quality items in the cylinders were measured.

2.5. Exposure Measurement and Analysis

In this study, we measured two things: the air quality inside the SCBA and the envi-ronment of the SCBA charging room.

The air quality inside the SCBA was measured for carbon monoxide (CO), carbon dioxide (CO_2), oil mist, and water vapor using a compression respiration test kit (CG-1, Gastec, Japan). PM (particulate matter) of 2.5 and 10, to compare the difference was measured using a Grimm Portable Aerosol Spectrometer (1109, Grimm GmbH, Germany). Particulate matter (PM2.5, PM10) and gaseous matter (TVOC, HCHO, HCN, NO, O_2, H_2S, CO, and LEL) were measured as indoor environmental measurement factors in the SCBA charging room at the fire station (Table 4). Appendix A shows the environmental characteristics of the SCBA charging rooms for the two onshore fire stations and two water rescue stations.

Table 4. Measurement items and analysis method.

Gaseous Materials	Measurement Range (ppm)	Model, Manufacturer
TVOC	PID	ppbRAE 3000, RAE
HCHO	0–10	ToxiRAE, RAE
HCN	0–50	ToxiRAE, RAE
NO	0–250	ToxiRAE, RAE
O_2	0–30%	QRAE 3, RAE
H_2S	0–100	QRAE 3, RAE
CO	0–500	QRAE 3, RAE
LEL	0–100%LEL	QRAE 3, RAE

TVOC: total volatile organic compounds; HCHO: formaldehyde; HCN: hydrogen cyanide; NO: nitric oxide; O_2: oxygen; H_2S: hydrogen sulfide; CO: carbon monoxide; LEL: lower explosive limit.

The statistical analysis tool used in this study was SAS version 9.4 (Cary, NC, USA). Statistical analysis was conducted using the Mann-Whitney U test (Wilcoxon Scores) method, which is a non-parametric method, to evaluate the statistical significance between groups.

3. Results

3.1. Result of SCBA Air Quality Analysis when Charged at the Land Fire Station

In two SCBA charging environments of the onshore fire station, the air quality components and charging environments used by firefighters at the fire scene were measured, and the mean difference between the different charging environments was confirmed. Table 5 shows the four SCBA air quality items and the charging environment measurement of SCBA results charged in the SCBA charging rooms of two fire stations on land. Control group (A) is the result of charging in an SCBA charging chamber in a location in a shielded from harmful substances. Cases (B to E) were measured in an SCBA charging room located in a place that was not completely blocked from harmful substances, and showed differences according to the degree of exposure to harmful substances. In particular, among the charged air quality components, CO was detected to be 20 times higher in E, which has the characteristics of emitting the most harmful substances, than in A, which was charged in an isolated place. In addition, among the charged air quality components, carbon dioxide was twice as high in E as in A. Similar results have been obtained for gaseous substances measured in a charging environment. TVOC was detected to be 1958 times, CO 18.7 times, NO 5.6 times, HCN 3.3 times, PM2.5 10.3 times, and PM10 2.2 times higher in E than in A (Table 5).

Table 5. Result of analysis of SCBA for firefighting charged at land fire station.

Distribution		Measurement	Control Group (A)	Case Group				χ^2	*p*-Value
				Group 1	Group 2	Group 3	Group 4		
				Baseline (B)	Euro 6 (C)	Euro 5~6 (D)	Euro 4~6 (E)		
Quantity of SCBA			3	3	3	3	3	None	None
Temperature (°C)			26.1	18.3	18.3	19.0	20.7	14.0	<0.01
Humidity (%)			28.0	27.0	28.0	29.0	30.0	14.0	<0.01
Charged SCBA cylinder air quality		Oil mist (mg/m^3)	0	0	0.2 ± 0	0.2 ± 0	0.2 ± 0	14.0	<0.01
		CO (ppm)	0	0	5.0 ± 0	5.0 ± 0	20.0 ± 0	14.0	<0.01
		Water (mg/m^3)	5 ± 0	0	15.0 ± 0	5.0 ± 2.9	0	10.7	0.02
Charging environment	Particulate matter (PM)	CO_2 (ppm)	600 ± 0	750 ± 0	750 ± 0	750.0 ± 0	1200 ± 173.2	13.9	<0.01
		PM2.5	80.7 ± 31.6	22.5 ± 2.6	33.0 ± 2.4	46.5 ± 7.6	232.8 ± 14.1	13.1	0.01
		PM10	112.3 ± 29.7	65.2 ± 12.1	55.2 ± 7.9	62.8 ± 13.1	245.2 ± 13.8	12.8	0.01
	Gaseous matter	TVOC(ppb)	0	439 ± 0	783.0 ± 75.9	1283.0 ± 0	1958.0 ± 678.5	13.1	0.01
		HCHO($\mu g/m^3$)	0	0.23 ± 0	0.21 ± 0.01	0.18 ± 0	0.16 ± 0.05	12.7	0.01
		HCN (ppm)	0	0.8 ± 0	0.53 ± 0.5	0	3.3 ± 1.3	12.4	0.01
		NO (ppm)	0	1.4 ± 0	1.8 ± 0	2.8 ± 0	5.6 ± 2.2	13.5	<0.01
		O_2 (%Vol)	20.9 ± 0	20.9 ± 0	20.9 ± 0	20.9 ±	20.6 ± 0.2	8.5	0.07
		H_2S (ppm)	0	0	0	0	0	-	-
		CO (ppm)	0	7 ± 0	11.7 ± 0.6	13.0 ± 0	18.7 ± 5.1	13.6	<0.01
		LEL (%)	0	0	0	0	0	-	-

SCBA: self-contained breathing apparatus; CO: carbon monoxide; CO_2: carbon dioxide; TVOC: total volatile organic compounds; HCHO: formaldehyde; HCN: hydrogen cyanide; NO: nitric oxide; O_2: oxygen; H_2S: hydrogen sulfide; LEL: lower explosive limit.

Table 6 shows the mean difference in the air quality components of the SCBA charged in different environments, based on isolated installation A. A is the result of charging in a completely isolated environment, and B is the result of charging in a normal environment in the SCBA charging room inside the garage of a fire station. B-A can be seen as a basic indicator showing the degree of contamination of the internal environment of the fire station. In the case of B-A (I), the air quality inside the charging SCBA cylinders showed little difference except that CO_2 was 150 ppm higher, whereas PM 220, TVOC 439, NO 1.4, and CO 7 were, respectively high in the charging environment. C-A (H) showed a difference in air quality inside the SCBA cylinder when the engine-level Euro 6 vehicle was started in an isolated environment. Oil mist was higher than I by 0.2 mg/m^3, CO by 4ppm, and water by 15 mg/m^3. When engine-level-Euro 6 vehicles were started, the SCBA internal air quality was higher in the three items than at normal levels. D-A (G) shows the difference in air quality inside the SCBA cylinder filled with engine-level-Euro 5–6 vehicles and in an isolated environment, respectively. CO was 5 ppm higher than I, and water was 5 ppm higher. E-A (F) shows the difference in the air quality inside the SCBA cylinder filled with engine-level-Euro 4–6 vehicles and in an isolated environment, respectively. CO was 20 ppm higher than I, CO_2 was 450 ppm higher, and PM2.5 and PM10 were 152.1 and 132.9 higher than I, respectively. As shown in Table 5, the mean difference in CO among the air quality components in the cylinder was higher for the SCBA filled in a place with more exposure to the polluted environment, which showed a dose-response tendency. CO_2 showed a mean difference four times higher than that in I, especially in F, which was the worst environment. Regarding the mean difference in the SCBA charging room environment, TVOC, NO, and CO showed a positive-response relationship in the E-A and B-A groups. For TVOC, when I was the standard, F was 4.5 times, G was 2.9 times, and H was 1.8 times higher. For NO, F was four times higher, G was two times higher, and H was 1.3 times higher. In CO, F was 2.7 times higher, G was 1.9 times higher, and H was 1.7 times higher (Table 6).

Table 6. Differences in the air quality of the onshore terminal SCBA charged in different environments.

Distribution		Measurement	Mean Difference			
			E-A (F)	**D-A (G)**	**C-A (H)**	**B-A (I)**
Number of Cylinders			6	6	6	6
Charged SCBA cylinder air quality		Oil mist (mg/m^3)	0.2	0.2	0.2	0
		CO (ppm)	20	5	4	0
		Water (mg/m^3)	−5	0	10	−5
		CO_2 (ppm)	600	150	150	150
Charged environment	Particulate Matter (PM)	PM2.5	152.1	−34.2	−47.7	−58.2
		PM10	132.9	−49.5	−57.1	−47.1
	Gaseous matter	TVOC (ppb)	1958	1283	783	439
		HCHO (μg/m^3)	0.16	0.18	0.21	0.23
		HCN (ppm)	3.3	0	0.53	0.8
		NO (ppm)	5.6	2.8	1.8	1.4
		O_2 (ppm)	−0.3	0	0	0
		H_2S (ppm)	0	0	0	0
		CO (ppm)	19	13	12	7
		LEL (%)	0	0	0	0

SCBA: self-contained breathing apparatus; CO: carbon monoxide; CO_2: carbon dioxide; A: control group; B: baseline; C: Euro 6 fire engine start up; D: Euro 5~6 fire engine start up; E: Euro 4~6 fire engine start up; TVOC: total volatile organic compounds; HCHO: formaldehyde; HCN: hydrogen cyanide; NO: nitric oxide; O_2: oxygen; H_2S: hydrogen sulfide; LEL: lower explosive limit.

Regarding the mean difference in the SCBA charging room environment, TVOC, NO, and CO showed a dose-response relationship in the E-A and B-A groups. In the case of TVOC, based on I, F was 4.5 times, G was 2.9 times, and H was 1.8 times higher. For NO, F was 4 times higher, G was 2 times higher, and H was 1.3 times higher. For CO, when I was used as the standard, F was 2.7 times higher, G was 1.9 times higher, and H was 1.7 times higher (Table 6).

3.2. Result of SCBA Air Quality Analysis when Charged at the Floating Fire Station

Table 7 shows the four SCBA and SCUBA air quality items and the charging environment in the SCBA/SCUBA charging stations of the two water rescue teams located on the water. Since the water rescue team uses two types of SCBA, they were measured separately for fire suppression and water rescue. The temperature of the charging space was higher when charging in an environment exposed to harmful substances than when charging in an environment blocked from harmful substances (control group), and carbon dioxide among the SCBA air components was higher. The water contents in all the filled SCUBA cylinders were higher than the normal range because the fire station of the water rescue team was close to the water. Carbon dioxide was higher in all the filled SCBA/SCUBA air components in the case group than in the control group (Table 7).

Table 7. Result of the SCBA air quality analysis when charged at the fire station of the water rescue team.

Distribution	**Measurement**	**Y FD**				**B FD**				χ^2	***p*-Value**
		SCBA for Firefighting		**SCUBA for Water Rescue**		**SCBA for Firefighting**		**SCUBA for Water Rescue**			
		Control Group	**Case Group**	**Control Group**	**Case Group**	**Control Group**	**Case Group**	**Control Group**	**Case Group**		
Number of Cylinders		3	3	3	3	3	3	3	3	None	None
Temperature (°C)		31.9 ± 0.8	34.6 ± 0.9	31.6 ± 0	33.5 ± 0	24.8 ± 0	26.9 ± 0.2	23.0 ± 0	25.7 ± 0	22.6	<0.01
Humidity (%)		45.0 ± 1.0	41.7 ± 1.1	49.0 ± 0	47.0 ± 0	49.0 ± 0	46.0 ± 0	49.0 ± 0	48.0 ± 0	22.8	<0.01
Charged SCBA air quality	Oil mist (mg/m^3)	0	0	0	0	0.13 ± 0	0.17 ± 0.06	0.4 ± 0.2	0.16 ± 0.06	21.5	<0.01
	CO (ppm)	0	0	0	5.0 ± 0	0	8.0 ± 1.0	0	8.7 ± 0.5	22.6	<0.01
	Water (mg/m^3)	60.0 ± 10.0	41.7 ± 2.9	51.7 ± 2.9	41.7 ± 2.9	30.0 ± 0	35.0 ± 5.0	33.3 ± 5.7	30.0 ± 0	20.5	<0.01
	CO_2 (ppm)	500.0 ± 0	583.3 ± 28.9	500.0 ± 0	533.3 ± 57.7	583.3 ± 28.8	783.3 ± 28.8	516.7 ± 28.8	783.3 ± 57.7	20.0	<0.01
Charging environment — Particulate matter (PM)	PM2.5	19.3 ± 3.8	18.1 ± 4	13.4 ± 0	16.7 ± 0	15.7 ± 3.5	14.5 ± 2.5	13.0 ± 0	14.6 ± 0	12.8	0.07
	PM10	23.6 ± 4.4	23.1 ± 5.2	16.1 ± 0	21.0 ± 0	22.7 ± 1.4	19.6 ± 3.5	20.0 ± 0	22.1 ± 0	15.5	0.02
Charging environment — Gaseous matter	O_2 (%Vol)	21.3 ± 0.3	20.9 ± 0	20.9 ± 0	20.9 ± 0	21.3 ± 0	21.4 ± 0	20.9 ± 0	21.3 ± 0.1	18.5	<0.01
	H_2S (ppm)	0	0	0	0	0	0	0	0	-	-
	CO (ppm)	0	0	0	0	0	0	0	0	-	-
	LEL (%)	0	0	0	0	0	0	0	0	-	-

FD: fire department; SCBA: self-contained breathing apparatus; SCUBA: self-contained underwater breathing apparatus; CO: carbon monoxide; CO_2: carbon dioxide; O_2: oxygen; H_2S: hydrogen sulfide; LEL: lower explosive limit.

Table 8 shows the mean differences in air quality inside SCBA/SCUBA charged by the 119 Special Rescue Services, Yeouido Water Rescue Team, and Banpo Water Rescue Team in environments exposed to hazardous substances and non-exposed environments for firefighting and water rescue use. There was a difference of 66.7 ppm in CO_2 in the SCBA for the fire measured at the Yeouido Water Rescue Station and a difference of 33.3 ppm in the SCBA for water rescue. The mean difference in CO_2 among the internal air quality components was twice as high during firefighting than during water rescue. In the case of CO, there was no difference in firefighting use, but there was a difference of 5 for water rescue use, with a value five times higher for water use than firefighting use. In the fire SCBA measured by the Banpo Water Rescue Team, CO_2 showed mean differences of 200 and 266.6 for firefighting and water rescue, respectively. In contrast, CO showed differences of 8 and 8.7, respectively. As a result of measuring the SCBA charging environment, the water rescue team had the environmental characteristic of the four sides being open; thus, gaseous substances were hardly detected (Table 8).

Table 8. Differences in SCBA and SCUBA air quality at waterfront buildings charged in different environments.

Distribution		Measurement	Mean Difference			
			YFD	YWD	BFD	BWD
Charged SCBA and SCUBA air quality		Oil mist (mg/m^3)	0	0	0.04	−0.3
		CO (ppm)	0	5	8	8.7
		Water (mg/m^3)	−16.7	−10	5	−10
		CO_2 (ppm)	66.7	33.3	200	266.6
Charging environment	Particulate matter	PM2.5	−1.2	3.3	−1.2	1.6
		PM10	−0.5	4.9	−3.1	2.1
	Gaseous matter	O_2 (%Vol)	−0.4	0	0.1	7
		H_2S (ppm)	0	0	0	0.4
		CO (ppm)	0	0	0	0
		LEL (%)	0	0	0	0

SCBA: self-contained breathing apparatus; SCUBA: self-contained underwater breathing apparatus; YFD: differences in measurement of SCBA for firefighting charged in exposed and non-exposed environments at Yeouido Water Rescue Station; YWD: difference in measurement of SCBA for water charged in exposed and non-exposed environments at Yeouido Water Rescue Station; BFD: difference in measurement of SCBA for fire charged in the exposed environment and non-exposed environment at Banpo Water Rescue Station; BWD: difference in measurement of respirators for water recharging in exposed and non-exposed environments at Banpo Water Rescue Station; CO: carbon monoxide, CO_2: carbon dioxide; O_2: oxygen; H_2S: hydrogen sulfide; LEL: lower explosive limit.

4. Discussion

In this study, experiments were conducted on issues ranging from the operation and management of SCBA chargers to the charging stage of SCBA as a charging cylinder. First of all, we would like to continue the discussion on the environment of the SCBA charging room installed and operated by the onshore fire station and the quality of the SCBA charging air.

4.1. Implications of the Effect of the Difference in the Air Charging Room Installation Environments on the Charging Air Components Inside the SCBA

For the SCBA charging room at the onshore fire station where this study was conducted, the case group conducted an experiment in which an SCBA charger was installed and operated in a location that was not blocked from harmful substances. There was no ventilation system, but the outlet was located immediately next to the charging chamber, so that the indoor air could be exhausted; however, there was an effect from the polluted air. This does not conform to the provisions of the above law. In addition, when the experiment was conducted in the control group, an SCBA charger was installed and operated in a separate temporary building space to block harmful substances; however, it was not equipped with a separate ventilation system and was configured to allow for exhaustion by opening and closing the door. The control group did not fully meet the statutory requirements. As a result, in the control group, where the air charging room was installed in a separate space, all of the SCBA air quality was measured within the safe range for OSHA, NFPA, and KOSHA, and in particular, CO was detected as 0. However, in the case group where the air charging room was located inside the garage, CO and CO_2 were detected in quantities that exceeded the safe range. In Group E, the CO and CO_2 components of the SCBA air quality exceeded the safe range compared to those OSHA. However, oil mist and water were both measured to be within the safe range of OSHA, NFPA, and KOSHA. Through this experiment, it was confirmed that the difference in the environment of the SCBA charging facility at the land fire station could affect the CO and CO_2 in the air, and therefore, the air quality inside the SCBA.

The United States stipulates the NFPA 1989 standard for the use, approval, and management of respiratory aids by emergency response personnel. The purpose of NFPA 1989 was to establish criteria for the safe supply of breathing air for emergency service personnel who use atmosphere-supplying respirators to provide life support during rescue and confined-space operations. In particular, Chapter 7, which was revised and added in 2019, recommended that installation, compression, maintenance, and the recording of air quality inspection results be organically and well operated to maintain the proper function of the SCBA system; it is emphasized that the air within the SCBA must not be polluted [28].

4.2. Absence and Current Reality of Air Charging Regulations for Fire Departments in Flooded Environments and Possible Problems

A water rescue station is a fire station in the shape of a barn located at sea level, and is surrounded by water on all four sides; thus, it is basically a high-humidity working environment. As can be seen from the results of this study, it was confirmed that the moisture content in the air in the SCBA cylinder filled in the SCBA charging room located at each of the two water rescue stations exceeded the safe range. Detecting moisture exceeding the standard for SCBA indicates that a problem may occur with the ability of the air charger to remove moisture. Rapid action is required as this is also related to the loss of function of SCBA charger purification material. In general, purification materials require proper management because they directly filter pollutants. As an additional problem that may occur, mold or bacteria inside the SCBA may proliferate because of moisture if proper intervention is not performed on the moisture content, including excess moisture in the cylinder. Alternatively, moisture can cause or accelerate the corrosion of SCBA cylinders. However, when firefighters use SCBA cylinders, the bacteria present in the air can enter the lungs through the respiratory tract and may cause respiratory diseases, including pneumonia. Long-term exposure to occupational environments can lead to work-related diseases [29].

Foreign substances have been detected in SCBA cylinders used by Korean firefighters, which has become a social issue. Aluminum oxide was found in the SCBA cylinder according to our cause analysis results. The biggest cause of oxidation is moisture, which can occur if the filter replacement cycle of the air charger is exceeded or if charging on a rainy day or in a state where the SCBA cylinder is not sufficiently dried. In some cases, it has been pointed out that rapid opening of the container valve and a decrease in temperature may cause this. In addition, if there is no pressure holding the valve behind the SCBA charger filter, moisture may be generated even when charging by connecting the cylinders with residual pressure. Therefore, it has been suggested that detailed measures are needed, such as closing the valve to prevent the inflow of impurities when storing cylinders or leaving a small amount of residual pressure when storing used cylinders. The research results and suggestions are included in the SCBA manual to guide firefighters in using and managing them safely [30,31].

The National Emergency Management Agency (NEMA), which has experienced controversy over aluminum oxide detection in SCBA in Korea in the past, enacted a type of approval standard for SCBA chargers in October 2007. Standards for the water content of the SCBA filter were set, and performance enhancements were included, such as installing a pressure-holding valve to prevent residual pressure from entering the filter.

In SCBA used during firefighting activities, the following elements need to be systematically and scientifically maintained to meet the safety level of the quality of air inhaled by firefighters: (1) installation and operation of an SCBA charging room installed in a hygienic environment that guarantees the health and safety of firefighters; (2) air compression from a normal atmosphere to the air charger; (3) SCBA charging in the charging cylinder; (4) air intake through the use of individual face shields at the fire scene; (5) regular SCBA air quality analysis, SCBA cylinder inspection and management; and (6) careful SCBA charging room environment management.

4.3. Chronic Exposure to CO in SCBA Charging Environments in Land-Based Fire Stations and the Risk Firefighters of Occupational Diseases

Indirect exposure or cross-contamination occurs in a garage within a fire station if emergency decontamination is not performed on a fire scene after firefighting activities. In particular, if the SCBA cylinder is charged in an unclean place at a fire station that is not blocked from smoke, it may affect the health of firefighters, including the respiratory system. It has been reported that the incidence of Parkinson's disease in firefighters exposed to CO is approximately 10 times higher than that in the general population, and it is known that it is related to work; therefore, it is necessary to minimize CO exposure even in small amounts in firefighters [32]. According to our results, when the SCBA was charged in an environment that was not completely blocked from harmful substances or smoke, the CO component in the SCBA cylinder exceeded the safe range. Epidemiological studies revealing the risk factors for Parkinson's disease in firefighters cannot be found in Korea or abroad. However, it has been reported that the risk of Parkinson's disease can be increased when we are exposed to CO, toluene, manganese, and lead, which are generated in various fires [33]. Therefore, installing an SCBA charger in a safe environment so that air components can be charged within a safe range can contribute to the prevention of occupational diseases by improving the long-term occupational environments of firefighters.

In the SCBA used by firefighters, compressed air is injected into a cylinder. However, it has been confirmed that compressed breathing air contains high levels of carbon monoxide (CO) and water vapor, associated with carboxyhemoglobin (COHb) poisoning and freezing of the SCBA user's controller. Therefore, firefighters using SCBA have proposed programs and SOPs to minimize the risk of exposure to contaminated air [34].

4.4. Increased Risk of Work-Related Respiratory Diseases among Firefighters

Activities that can damage the respiratory system of firefighters and allow harmful substances to enter the human body can be classified into three categories. First, thermal hazards include thermal rise due to oxygen deprivation, rollover, flashover, and backdraft. The second is caused by toxic gases and smoke, such as CO, hydrogen chloride, hydrogen cyanide, CO_2, phosgene, nitrogen dioxide, acrolein, formaldehyde, hydrogen sulfide, sulfur dioxide, and benzene. Both of these can pose a risk to the respiratory system during a fire. The last category is not related to fire but can affect the respiratory system, and includes asbestos, polyvinyl chloride (PCB), hazardous materials, biological and medical pathogens, and weapons of mass destruction [35–37].

Firefighters must protect their respiratory systems by wearing SCBA in various disaster situations and fires. During firefighting, firefighters may experience occupational exposure to gases, chemicals, particulates, and other substances that can cause short- and long-term damage to the respiratory system. According to previous studies conducted on firefighters, firefighters may be exposed to toxic and respiratory irritants including sulfur dioxide, hydrogen chloride, phosgene, nitrogen oxides, aldehydes and particulates [38,39]. The combustion of building materials produces numerous combustion products, and the production of numerous new commercial compounds each year is one of the causes of genotoxicity and increases the risk of respiratory problems in firefighters. The Ministry of Health and Safety of the International Association of Fire Fighters (IAFF) state that the risk of acute lung disease increases during firefighting. In addition, it has been reported that surviving firefighters who were dispatched to the scene of the 9/11 terrorist attacks that occurred at the Twin Towers in New York in 2001 have various types of respiratory diseases such as asthma, chronic obstructive pulmonary disease (COPD), acute rhinitis, and lung diseases including sore throat [40–42].

Despite the improvement in personal protective equipment including SCBA, the incidence of cancer in firefighters is increasing and is known to be a major cause of death. Several epidemiological studies have confirmed that the risk of cancer is higher in firefighters than in the general population. In particular, immune regulation disorders increase when exposed to a fire scene overhaul environment or fire investigation without respiratory protection, thereby increasing the risk of lung disease and cancer [43–47]. Therefore, it is necessary to minimize occupational exposure of the respiratory system during firefighting, and to manage the charging environment so that the air in the SCBA used to protect the respiratory system can be maintained within a safe range.

4.5. Efforts and Implications for Prevention of Occupational Respiratory Diseases among Firefighters

Firefighters are an occupational group that is repeatedly and continuously exposed to combustible substances generated during disasters such as fires [48]. Because the dust generated at the firefighting activity site is absorbed through the respiratory system and skin, wearing respiratory protective equipment at the accident scene is very important and directly related to life. The American Lung Association suggested that short-term exposure to problems such as smoke inhalation during firefighting stimulates the airways, and has adverse health effects such as coughing, wheezing, shortness of breath, and the exacerbation of lung diseases such as asthma, and bronchitis. In addition, long-term exposure to the respiratory system increases the risk of death from cancer, including lung cancer. As firefighting activity increases, the risk of death from chronic obstructive pulmonary disease increases [49].

Several studies have been published that have confirmed the occurrence and risk of work-related respiratory diseases among firefighters. In a cohort study conducted at the University of Chicago with 76 firefighters, reductions in FVC and carbon monoxide diffusion volume were confirmed compared to the general population, and lung cancer and COPD were observed in firefighters and first responders who were active at the World Trade Center (WTC) terrorist scene. Asthma, chronic bronchitis, pulmonary fibrosis, and sarcoidosis were associated with firefighters responding to disasters [50]. Firefighters who experience extensive exposure to wildfire scenes were associated with non-resolving airway damage [51]. It was confirmed that lung function (FEV1, FVC, and FEV1/FVC) was reduced in the pulmonary function evaluation of US firefighters who were followed up for five years. We emphasize the importance of wearing respiratory protective equipment to minimize the risk of lung damage [52]. In particular, firefighters showed an accelerated rate of decline in lung function shortly after exposure to a major event. In a study comparing respiratory health between firefighters and the general population, respiratory symptoms and atopy were higher in firefighters than in the general population [52]. The bronchial hyperreactivity odds ratio of methacholine was 2.24 (95% confidence interval 1.12–4.48). However, this was not related to acute exposure or the length of service [53].

Therefore, health authorities in many countries recommend the following measures to mitigate the health risks to firefighters of respiratory-related occupational exposure:

1. In the overhaul phase of the fire scene, personal protective equipment, including that used for breathing should be carefully worn and firefighting activities should be performed.
2. Firefighters performing firefighting duties must receive repeated training on how to minimize occupational exposure to harmful chemical agents, and government agencies, such as the National Fire Service, must develop and provide training programs.

3. Job-related exposure to pulmonary irritants outside of work should be reduced. Firefighters should not smoke or vape, and should avoid secondhand smoke whenever possible.

4.6. Strengths, Limitations and Further Study

Studies related to SCBA are focused on the corrosion of the metal surface inside a compressed air cylinder for air-breathing due to moisture, the comparison of compressed air standards, and abnormal symptoms when wearing SCBA. Through an experiment to identify the cause of SCBA container corrosion and SCBA container management, a Delphi investigation study was conducted for the actual condition investigation and improvement of SCBA and SCBA charging room management systems. However, no study has evaluated the air quality inside an SCBA cylinder due to the differences in SCBA charging environments. In particular, the significance of this study lies in the fact that no studies have yet conducted experiments on either land or water fire stations.

This study has several limitations. First, since the results were derived for two land and two water fire stations, the results cannot be generalized. Therefore, follow-up studies should be conducted to ensure that the results are representative. Second, in the case of the land fire station, the differences in model types of SCBA charging equipment were not reflected. Third, in the case of the experiment conducted in charging rooms that were not completely isolated in the on-land fire station, considering not only the smoke emitted from the fire truck, but also the possibility of harmful substances generated by taking off contaminated PPE in the garage of the fire station when returning home from a fire dispatch could not be measured. Therefore, there is a possibility of underestimation. A follow-up study will be needed.

This experimental study was conducted at four fire stations and confirmed that the SCBA charging environment could affect the air quality inside the SCBA. From this result, it can be inferred that the long-term inhalation of contaminated air inside SCBA may cause adverse health effects. In the future, chronic health effects may be identified through long-term health follow-ups of firefighters who work at fire stations where SCBA charging stations are not completely isolated from soot and harmful substances [54]. Importantly, based on the results of this study, active efforts by policy makers are needed to improve the environment of SCBA charging facilities. In the case of fire stations being newly built or remodeled in the future, the results of this study on SCBA charging facilities and architectural designs that comply with related laws and regulations should be reflected for the health and safety of firefighters.

5. Conclusions

To evaluate the internal air quality of SCBA, which firefighters use as essential respiratory protection equipment in fire scenes, a simulation-based case-control experiment was conducted in SCBA charging rooms on land and water. The SCBA charging rooms were stratified according to their degree of exposure to harmful substances, and the situation was set, measured, and analyzed. As a result of the SCBA test at the land fire station, when the SCBA charging room, which was completely isolated from harmful substances, was installed as a standard, CO among the air quality components inside the SCBA cylinder in the exposed group was detected in an amount exceeding the safe range twice. In the SCBA cylinders charged at the floating fire station for fire and water use, all water components exceeded the safe range regardless of exposure to harmful substances. However, in the floating firefighting building, CO was not detected in the air inside the SCBA cylinder even in an environment where the SCBA charging room was exposed to harmful substances, which can be assumed to be well-ventilated because of the characteristics of the building in which all four sides are open.

According to the results of this study, chronic exposure to high CO levels inside SCBA can cause occupational diseases, and water components higher than the standard can cause respiratory diseases by corroding the inside of the SCBA or leading firefighters to inhale viruses and bacteria. It was found that the installation environment of the SCBA charging room in a fire station is very important. A poor working environment can threaten the health and safety of emergency workers and firefighters; therefore, systematic operation and thorough management are very important. Relevant laws and regulations have already stipulated the requirements of the SCBA charging room. However, the fact that they have not yet been applied in reality can also indicate a poor working environment in fire stations. Therefore, this study can be used in the future to establish measures for improving the occupational environments of SCBA charging rooms installed and operated by fire stations.

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Appendix A

Table A1. Overview of the SCBA Charger Used in the SCBA Experiment.

No	Fire Department	Production Country	Manufacturer	Product Model	SCBA Installation Location
1	Guro fire station, emergency response team	Republic of Korea	MSL Fire	M15	Inside the fire station garage (not blocked from harmful substances)
2	Guro fire station, Sindorim 119 Safety Center	Republic of Korea	MSL Fire	MSF1600KFI	Separate space (not blocked from harmful substances)
3	119 Special Rescue Services, Yeouido Water Rescue Team	Italy	COLTRL	MCH30	Storage inside fire station (there is a hinged door that can block harmful substances)
4	119 Special Rescue Services, Banpo Water Rescue Team	Republic of Korea	MSL Fire	M15	Storage inside fire station (there is a hinged door that can block harmful substances)

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