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Are loose-fitting powered air-purifying respirators safe during chest compression? A simulation study

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ABSTRACT

Background: The application of appropriate personal protective equipment for respiratory protection to health care workers is a cornerstone for providing safe healthcare in emergency departments. We investigated the protective effect and usefulness of loose-fitting powered air-purifying respirators (PAPRs) during chest compression.
Methods: This was a single-center simulation study performed from May 2019 to July 2019 in a tertiary hospital. We measured the concentrations of ambient aerosol and particles inside the loose-fitting PAPR during chest compression, and this ratio was set as the simulated workplace protecting factor (SWPF). According to the National Institute for Occupational Safety and Health regulations, the assigned protection factor (APF) of loose-fitting PAPRs is 25. Thus, the loose-fitting PAPRs were assumed to have a protective effect when the SWPF were ≥ 250 (APF × 10). We measured the SWPF of PAPR in real time during chest compression and also investigated the problems encountered during its use.
Results: Ninety-one participants (median age 29 [interquartile range (IQR): 26–32] years; 74% female) completed the simulation. None of the participants failed with SWPF below 250 during three sessions of chest compression. The median (IQR) values of SWPF at three cycles were 17,063 (10,145-26,373), 15,683 (9477-32,394), and 16,960 (7695-27,279). There was no disconnection of equipment or mechanical failures during chest compression. In addition, most participants (83%) replied that they rarely or never experienced difficulty in verbal communication and felt that the loose-fitting PAPR was comfortable.
Conclusions: The loose-fitting PAPRs provided sufficient respiratory protection without disturbances during chest compression.

1. Introduction

In modern medicine, infection prevention and control measures are of central importance to the safety of patients, healthcare workers (HCWs), and the community [1]. Emergency departments (EDs) are the principal portals of entry into healthcare systems, and the appropriate use of personal protective equipment (PPE) is one way to further reduce the risks of infection transmission [2,3]. The severe acute respiratory syndrome (SARS) and the Middle East respiratory syndrome coronavirus (MERS-cov) outbreaks have recently raised concerns of airborne transmission in the healthcare settings [4-6]. The World Health Organization (WHO) has recommended the use of particulate filtering facepiece respirators such as N95 filtering facepiece respirator (N95 respirator) or their equivalent when HCWs treat patients with airborne infectious diseases, but facepiece respirators only work properly when the face seal is tight [1]. Cardiopulmonary resuscitation (CPR) is a life-saving procedure that is frequently performed in the ED. Chest compressions, one of the main components of CPR, needs intense and dynamic movements. Previously published simulation studies showed that the N95 respirator did not provide adequate protection during chest compression [7].

According to the National Institute for Occupational Safety and Health (NIOSH) regulations, powered air-purifying respirators (PAPRs) are specified for high-hazard procedures (e.g., sputum induction, bronchoscopy, administration of aerosolized medication), because they can offer higher assigned protection factors (APFs) ranging from 25 to 1000 than N95 respirators (APF = 10) [8]. A PAPR is a battery-powered blower that provides clean air through a canister or cartridge

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with filter to the different type of hoods such as tight-fitting respirator, a loose-fitting hood, or a helmet. In the medical environment, loose-fitting PAPR is mainly used because it can cover the entire face including the eye and it also does not require a fit test [9,10].

To date, there are no standardized recommendations in the international CPR guidelines for the level of protective equipment that HCW should wear during CPR when treating patients with airborne diseases. Since 2015, the Korea Centers for Disease Control and Prevention (KCDC) has revised its guidelines for patients with suspected MERS to use PAPR during CPR [11]. However, there is insufficient evidence on whether loose-fitting PAPRs provides and maintains a protective effect for HCWs during CPR. In addition, because PAPR is a multi-piece equipment with external connections through an unfixed tube, there are concerns about the possibility of equipment problems such as tube disconnection and fan malfunction due to intense movements during chest compression. Finally, PAPR may affect the satisfaction and performance of participants who perform chest compression.

The purpose of this study was to investigate the protective effect of loose-fitting PAPRs during chest compressions. We also evaluated the user experience of the participants and the presence of any device problems.

2. Materials and methods

2.1. Study design and setting

This was simulation study in a single center from May 2019 to July 2019. The study was conducted in an isolated room located in the ED which has identical conditions to manage patients with infection in Samsung Medical Center (a tertiary hospital located in Seoul, a capital city of South Korea). Temperature and humidity were controlled at approximately 23 °C and 30%, respectively. The institutional review board of our institution approved the study, and a written informed consent was obtained from each participant.

2.2. Selection of participants

HCWs who met all the following criteria were eligible for inclusion: 1) 20 years of age or older; 2) those certified for the delivery of basic life support or advanced cardiovascular life support by the American Heart Association (AHA) or Korean Association of Cardiopulmonary Resuscitation, or those who had completed our institutional training program for CPR. Participants with conditions that could cause harm to their health due to chest compressions such as pregnant, having asthma, coronary heart disease, and musculoskeletal diseases were excluded from the study.

2.3. Measurements

2.3.1. Preparation for simulation

Investigators briefly explained to the participants the entire simulation process (Fig. 1). The Resusci Anne manikin (Laerdal Medical, Stavanger, Norway) was used for the chest compressions. The participants were familiar with this manikin because it is used for regular CPR training of HCWs in our institution. Subsequently, all participants were trained on how to use PAPR. They checked the components of PAPR, connected the equipment, and practiced donning and doffing in equipment. Participants completed a questionnaire to collect data on their demographic characteristics.

2.3.2. A loose-fitting powered air-purifying respirator

The PAPR equipment used in this study consisted of a Jupiter powered air turbo, breathing tube (BT-20 L) and loose-fitting hood (S-433 L-5) (3 M, St. Paul, MN) (Fig. 2). The manufacturer's recommended air flow rate of the Jupiter powered air turbo is between 150 L/min and 230 L/min; thus, we maintained the flow above

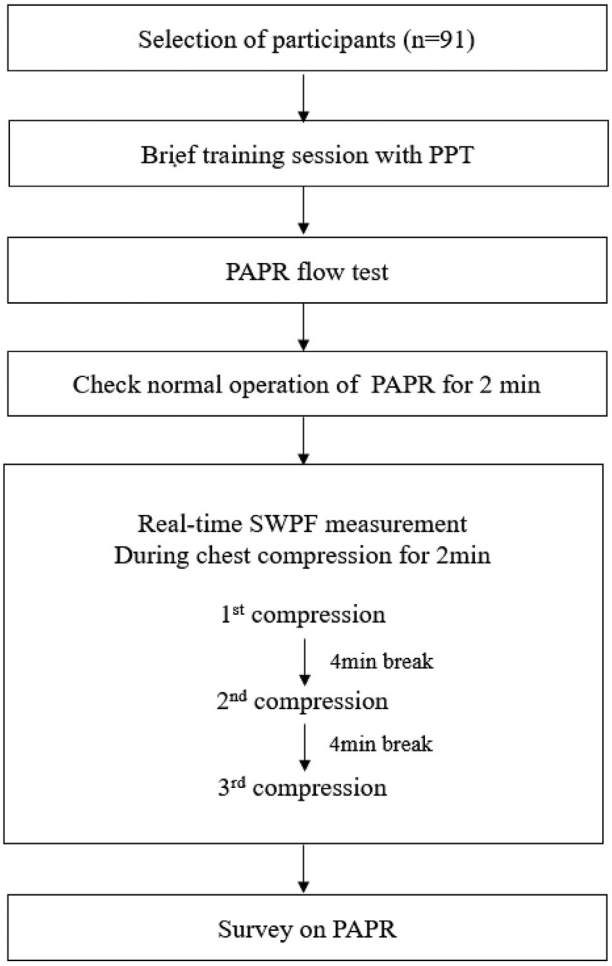

Fig. 1. Flow of simulation. Abbreviations: PPT, power point; PAPR, powered air purifying respirator; SWPF, simulated workplace protection factor.

170 L/min in accordance with the NIOSH guidelines for loose-fitting PAPR [10]. This equipment was certificated by the British Standards Institution (BSI), 539745 CE. The PAPR includes a particle filter P3 to protect against particles, including highly toxic materials. During the simulation, we used a rechargeable battery (5.2 V, NiMH) that lasted 8 h when fully charged. The participants checked the operational state of the PAPR themselves including the filter's fitting status and flow test under supervision of the investigators. In order to pass the flow test, the ball in the cylinder had to rise above a specific line defined by the manufacturer. Only the device that passed the test was used for the simulation. After flow test, they were equipped with the PAPR and confirmed that there is no problem in operation for 2 min. If any abnormality was found in operation, the equipment was readjusted or changed.

2.3.3. Assigned protection factor of loose-fitting PAPRs

The NIOSH has published and enforced APF for respiratory protective equipment. The APF means the workplace level of respiratory protection that certain respirator is expected to provide to workers. The APF for PAPRs vary from 25 to 1000 depending on the type of facepiece selected (half mask, full facepiece, helmet/ hood, or loose-fitting facepiece), while APF of loose-fitting PAPRs is 25 [8]. The fit factor (FF) representing the concentration ratio in and out of the respirator was must exceed the APF by at least ten times in order for the fit to be deemed adequate [8,12]. Therefore, the loose-fitting PAPRs were assumed to have a protective effect when the FF ≥ 250.

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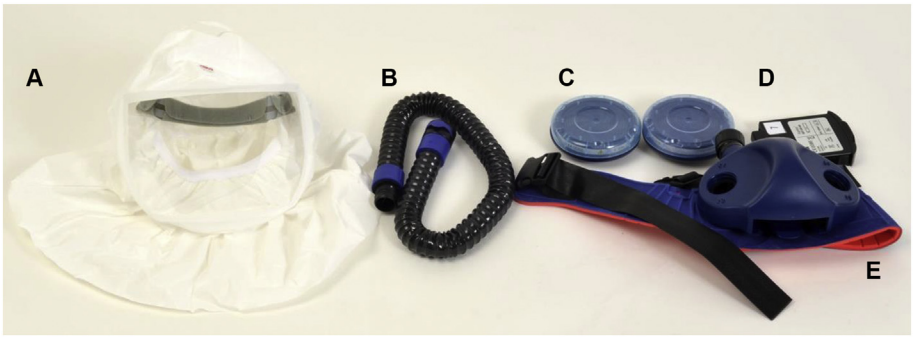

Fig. 2. A loose-fitting PAPR. *(A)* loose-fitting hood (S-433 L-5) *(B)* breathing tube (BT-20 L) *(C)* P3 particulate filter *(D)* 8 h battery (5.2 V, NiMH) *(E)* Jupiter powered air turbo (3 M, St. Paul, MN). Abbreviations: PAPR, powered air-purifying respirator.

2.3.4. Simulated workplace protecting factor measurement during chest compression

We measured the concentrations of ambient aerosol and particles inside the loose-fitting PAPR's hood during chest compression, and this ratio was set as the simulated workplace protecting factor (SWPF). We used a TSI model 8026 particle generator (TSI Inc., Shoreview, MN) to generate sodium chloride aerosol and the PortaCount Pro+8038 Respirator Fit Tester (TSI Inc., Shoreview, MN) was used to measure the SWPF in this simulation. We placed the ambient tube outside of hood, and the inlet of the respirator tube was placed at the midpoint between the participant's mouth and bottom of the nose. In real-time mode, SWPF was continuously recorded every second.

The participants performed continuous chest compressions without ventilation on the manikin in 2-min sessions, with 4-min rest between the sessions, while measuring SWPF in real time (Fig. 3). The participants either used footrests or knelt on the bed on the right side of the manikin depending on their preference. Participants wore PAPR until the end of the simulation and were not allowed to touch or manipulate the PAPR. Participants were asked to inform the investigator when they felt that there was no air flow in the hood or the connection tube was dislodged. All CPR quality data were collected using a Laerdal PC Skill Reporting System (Laerdal Medical). To control the high CPR quality according to the AHA guidelines, one investigator watched a computer monitor and provided feedback to each participant in real time [13].

2.3.5. PAPR survey

The survey had 9 questions about PAPR use by a 5-point Likert scale. After completing the simulation, participants were asked about the degree of comfortability to don or doff, difficulty to breathe through the PAPR, obstruction of vision, interrupting communication, skin irritation, and interference with ability. The investigators asked the participants three questions to assess the difficulty in communication during the 2-min operation time. The investigators gave feedback to the participants in real time to maintain the participants' CPR quality during the chest compressions. Based on the above, the participants subjectively assessed the difficulty in communication or listening after the simulation.

2.4. Outcome measures

The primary outcome was any failure of protection (SWPF <250) during three sessions of chest compression. The secondary outcome was device problem including tube disconnection or mechanical failures during the simulation and level of user experience of the participants.

2.5. Data analyses

A sample size calculation was made in terms of primary outcome achievement. To achieve a ratio of the fit factor of PAPR >250 of 99% in 95% confidence interval within ±5% by Clopper-Pearson's interval, 91 participants were required [14]. Standard descriptive statistics were used to present all data. Categorical variables are presented as number with percentages. Continuous variables are given as medians with interquartile ranges (IQRs). We estimated the smoothing graph for each individual SWPF and the mean SWPF during chest compression for each

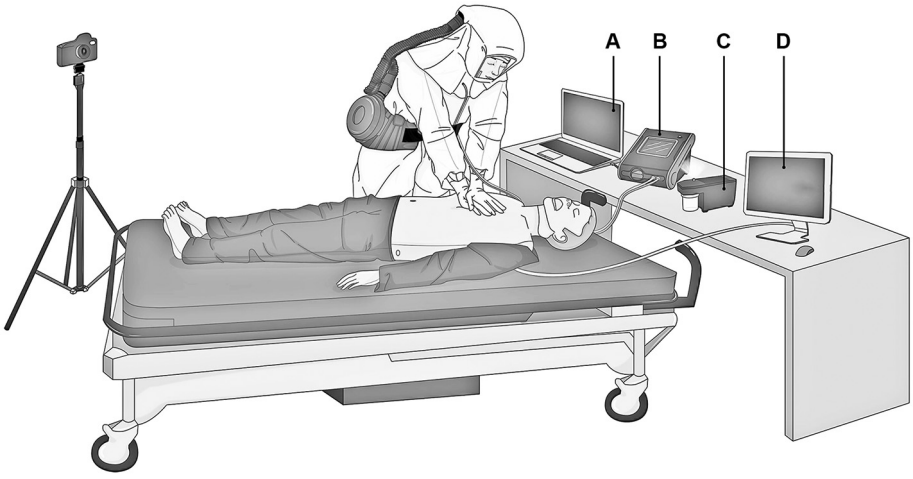

Fig. 3. Simulation. *(A)* SWPF real-time monitor *(B)* SWPF tester (PortaCount Pro+8038) *(C)* particle generator (TSI model 8026) *(D)* CPR quality monitor.

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Table 1
Baseline characteristics.

	Participants (n = 91)
Sex, female	67 (74)
Age (years)	29 (26–32)
Career (years)	4 (2–5)
Occupation	
Medical doctor	41 (45)
Registered nurse	44 (49)
Emergency medical technician	6 (6)
CPR training	
ACLS or BLS provider	76 (83)
KALS	1 (1)
Institutional program	14 (16)
BMI (kg/m^2)[a]	
Underweight (<18.5)	7 (8)
Normal (18.5–24.9)	72 (79)
Overweight (25.0–29.9)	11 (12)
Obese (≥30)	1 (1)

Data are shown as median with interquartile range or n (%).
Abbreviations: CPR, cardiopulmonary resuscitation; ACLS, Advanced Cardiac Life Support; BLS, Basic Life Support; KALS, Korean Advanced Life Support; BMI, body mass index.
[a] Body mass index was categorized according to the World Health Organization classification system.

time with the spline function (smoothing parameter = 0.3). Analyses were performed with STATA statistical software, version 15.0 (STATA Corporation, College Station, TX).

3. Results

3.1. Characteristics of study subjects

Overall, 91 participants completed the simulation. Table 1 presents the demographic characteristics of the study participants. Sixty-seven (74%) of the participants were female, and the median age was 29 (IQR: 26–32) years. Occupations of participants were medical doctors (n = 41; 45%), nurses (n = 44; 49%), and emergency medical technician (n = 6; 6%). Most participants were certified as ACLS or BLS providers (n = 76; 83%) by AHA, and 79% of the participants had a normal body mass index.

3.2. Chest compression quality

During the simulation, the quality of the chest compression including rate, depth, recoil, and correct hand position met the criteria of high quality CPR according to the 2015 AHA guidelines.

3.3. Outcomes

The primary outcomes are shown in Table 2 and Fig. 4. None of the participants had their SWPF below 250 during three sessions of chest compression. The median value (IQR) of SWPF was 17,063 (10,145-26,373) in the first session, 15,683 (9477-32,394) in the second session, and 16,960 (7695-27,279) in the third session. SWPF changes over time using the locally estimated scatterplot smoothing (LOESS) method did not show any particular pattern for the first, second and third SWPF during chest compression (Fig. 4).

Two cases of flow test failure and one case of tube disconnection occurred during the preparation and 2-min operation time; therefore, the investigators changed the equipment or adjusted the connection of the tube. However, there were no tube disconnections or machine failures during the chest compressions.

The survey of user experience on the loose-fitting PAPR is shown in Table 3. Most participants responded that the loose-fitting PAPR was comfortable to don (86%) and to doff (89%). The majority of participants rarely or never experienced difficulty breathing through the PAPR (93%) and did not experience fear or anxiety (90%). Seventy-six (83%) respondents reported that they had little or no difficulty in verbally communicating but 22 (24%) answered that they had difficulty in listening when wearing PAPR. For the questionnaire about whether PAPR interfered with the ability to do chest compression, 74 (81%) stated rarely or never had such an experience.

4. Discussion

None of the participants dropped their SWPF below 250 within total of 360 s during three sessions of chest compression in the simulation. Furthermore, during the three sessions of chest compressions, the median SWPF values of loose-fitting PAPR was over 15,000. A previous simulation study showed that the N95 respirator failed to provide sufficient protection, with the fit factor falling below 100 in 73% of participants during chest compressions [7]. This study demonstrates the safety of respiratory protection when the loose-fitting PAPR is used in chest compressions, thereby showing significant implications for the safety of HCWs and the reduction of risks of transmission of respiratory pathogens.

While several studies have evaluated the performance of the N95 respirators [7,15,16], only a few investigations have addressed the protection offered by the PAPRs. Gao et al. [12] evaluated the protection level of improperly sized loose-fitting PAPR using a manikin. The manikin fit factor values of the stretched-out and improperly sized loose-fitting facepieces were significantly lower than those obtained for the undamaged facepieces; thus, the former is unlikely to provide an acceptable level of protection. They suggest that loose-fitting facepieces are properly sized to employees and remove stretched-out facepieces from the workplace. In the study of Cohen et al. [17], they obtained SWPFs for five PAPR models representing different brands and facepiece styles. These respirators were tested on 12 volunteers performing 12 exercises to simulate real workplace activities. The SWPF range for the loose-fitting hooded PAPRs was 240 to >250,000, suggesting a high degree of protection as well as a large variance among the SWPFs. However, these activities did not include chest compressions, and our study examined for the first time the stability of loose-fitting PAPR in chest compressions.

A study reported the case of a HCW being infected after pathogen exposure due to disconnection of the circuit of PAPR during the outbreak of MERS-CoV in 2015 [18]. Since PAPRs are battery-operated to filter out contaminated air, malfunctioning machine, e.g., the disconnection circuit, battery discharge, and problems with the filter can be fatal. In this study, there were no cases of disconnections or mechanical failures during chest compression. However, during the preparation and 2 min operation time, there were three cases that failed the flow test or had a disconnected circuit, so the investigator adjusted connection of tube

Table 2
Primary outcome.

Chest compression	Ambient	Mask	Fit factor
First session	4260 (2377–7445)	0.34 (0.20–0.52)	17,063 (10,145–26,373)
Second session	4251 (1913–6510)	0.31 (0.18–0.49)	15,683 (9477–32,394)
Third session	3627 (1745–6622)	0.29 (0.18–0.43)	16,960 (7695–27,279)

Data are shown as median with interquartile range.

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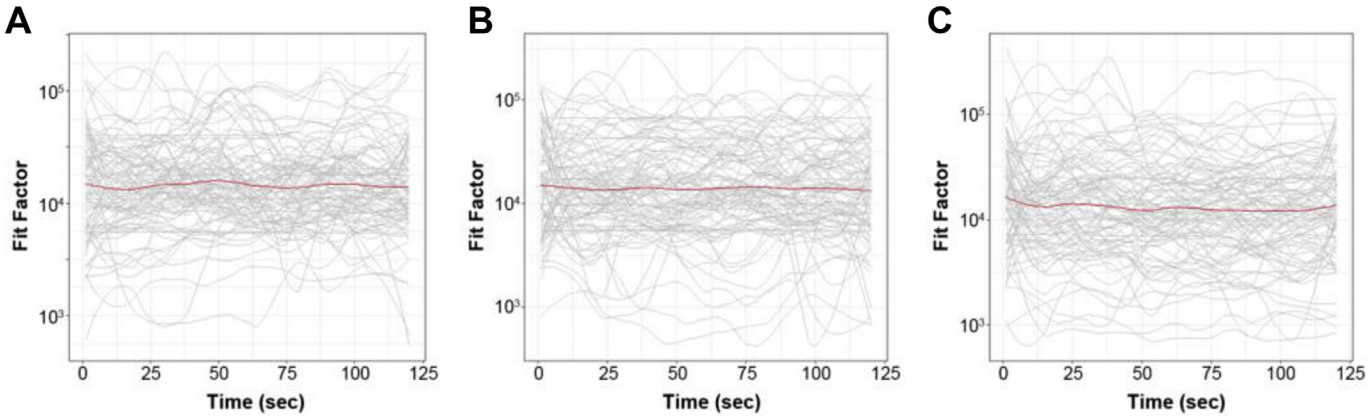

Fig. 4. The SWPF pattern of each participant over time. *(A)* first chest compression *(B)* second chest compression *(C)* third chest compression. Graphs show the pattern of SWPF change over time by using locally estimated scatterplot smoothing method. Abbreviations: SWPF, simulated workplace protection factor.

or changed the equipment. This suggests that it is important to perform flow testing and to check the operation during the preparation process. In addition, HCWs need to be trained regularly to use PAPR well in clinical setting and provided the proper instructions to become familiar to use.

Loose-fitting PAPRs utilize a motorized fan to draw air through the respirator's air purifying elements, delivering clean air to the wearer through a facepiece that does not form an airtight seal with the wearer's face. There is a concern about potential risk of wearer exposure to contaminants if the breathing rate of the wearer exceeds the air flow rate supplied by the PAPR fan [9,12]. In such an instance, ambient air could bypass the filters and enter the mask potentially exposing the wearer to contamination. Moreover, chest compressions are dynamic and fast that the inhalation flow during higher work rates could exceed the air flow supplied by the PAPR. Mackey et al. [19] measured overbreathing in one type of loose-fitting PAPR. Their measurements showed that even when peak inspiratory flow rate exceeded the blower flow rate, the concentration of aerosol within the PAPR remained below 0.1% of the ambient concentration. Thus, they assumed that the hood contributed a large dead volume that acted as a buffer against inward leakage of ambient aerosol. In this study, none of the participants dropped their SWPF below 250 within total 360 s. However, one participant showed fluctuations in SWPF values from 1442 to 2,883,675 at the first chest compression. Therefore, during chest compression, increasing the flow rate of the loose-fitting PAPR could help maintain positive pressure. However, the further studies of different blower flow rates are needed to better understand the effect of the over breathing.

In previous studies, loose-fitting PAPRs were considered more comfortable than N95 respirator because they reduce breathing effort and temperature with cool airflow and do not require a fit test, as well as have wide protection through the head, hair, eye, and neck [20,21]. However, it has been a concern that overall protective facemasks as loose-fitting PAPRs could impair communication [22]. In our survey, most of the participants (83%) responded that they rarely or never experienced difficulty in verbal communication. Besides the protective effect, the convenience of PAPR is important because it affects work performance. In this study, most participants (81%) did not think that the loose-fitting PAPR interfered with the ability to perform chest compression. Therefore, the findings of this study support the safety and convenience of the loose-fitting PAPR during chest compressions. However, 22 (24%) of participants responded that they had difficulties listening "most of the time or always". In actual clinical situations that require more communication and various roles, these difficulties could be greater. Therefore, training for HCWs and further research are needed to facilitate communication and work performance when wearing PAPRs.

4.1. Limitations

First, although we performed this study in actual ED settings to reflect real-life clinical situations, simulation environments have inherent limitations. Performing chest compressions on a manikin lacks patient interaction. In addition, the participants only performed continuous chest compressions without ventilations. CPR is a complex intervention in the clinical setting. Several tasks are performed by HCWs in an uncontrolled and confusing environment. Interactions with other HCWs during chest compressions in a realistic situation may affect outcomes including device problems (i.e., tube disconnection or mechanical

Table 3
Survey on loose-fitting PAPR.

Question	Scale[a]		
	1–2	3	4–5
1. Is it comfortable to don?	6 (7)	6 (7)	79 (86)
2. Is it comfortable to doff?	4 (4)	6 (7)	81 (89)
3. It obstructed my vision.	65 (71)	21 (23)	5 (6)
4. It is difficult to breathe through PAPR	84 (93)	4 (4)	3 (3)
5. It causes fear and anxiety	82 (90)	6 (7)	3 (3)
6. It was difficult to communicate verbally	76 (83)	8 (9)	7 (8)
7. It led to difficulty listening	56 (62)	13 (14)	22 (24)
8. It caused skin irritation	77 (84)	9 (10)	5 (6)
9. It interfered with my ability to do chest compression	74 (81)	9 (10)	8 (9)

Data are shown as n (%). PAPR, Powered Air Purifying Respirators.
[a] On a 5-point Likert scale, in which 1 = never, 2 = rarely, 3 = sometimes, 4 = most of the time, 5 = always.

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failures) and difficulties in communication. Second, we evaluated only one PAPR model and one-sized loose-fitting hood manufactured by one company. In particular, there was no consideration of each participant's face size. Therefore, there is a limit to generalizability of our results to other models. Third, we did not consider the infections associated with donning and doffing of PAPR and disinfection of equipment. Forth, we performed a flow test before the simulation, but the blower flow rate in hood was not measured in real time. Moreover, the filtration efficiency of PAPRs filter was not evaluated in this study. Finally, CPR quality may be affected by the use of PAPRs. However, our study aimed to assess the effect of PAPRs on respiratory protection during chest compressions and not on the quality of the chest compressions. Therefore, we provided feedback to each participant in real time to ensure high CPR quality to reflect real-world situations. Further studies are needed to determine the impact of PAPR use on the quality of chest compressions.

5. Conclusion

In conclusion, the loose-fitting PAPRs provided sufficient respiratory protection and comfort during chest compression. Further studies are needed to provide generalized guidance on the level of respiratory protection during CPR for patients with airborne diseases using several types of PAPRs in different CPR activities.

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Author contributions

Conceptualization: Yoon H, Hwang SY. Simulation: Yoon H, Hwang S, Park SH. Writing - original draft: Park SH, Yoon H, Hwang SY. Writing - review & editing: Yoon H, Hwang SY, Park SH, Kim T, Lee G, Park JE, Shin TG, Sim MS, Jo IJ, Kim S. Study supervision and approval of final manuscript: Yoon H, Hwang SY.

Declaration of competing interest

The authors have no potential conflicts of interest to declare.

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