Protective effect of tight-fitting powered air-purifying respirators during chest compressions

Abstract

Background: Airborne personal protective equipment is required for healthcare workers when performing aerosol-generating procedures on patients with infectious diseases. Chest compressions, one of the main components of cardiopulmonary resuscitation, require intense and dynamic movements of the upper body. We aimed to investigate the protective effect of tight-fitting powered air-purifying respirators (PAPRs) during chest compressions.

Methods: This single-center simulation study was performed from February 2021 to March 2021. The simulated workplace protection factor (SWPF) is the concentration ratio of ambient particles and particles inside the PAPR mask; this value indicates the level of protection provided by a respirator when subjected to a simulated work environment. Participants performed continuous chest compressions three times for 2 minutes each time, with a 4-minute break between each session. We measured the SWPF of the tight-fitting PAPR during chest compression in real-time mode. The primary outcome was the ratio of any failure of protection (SWPF < 500) during the chest compression sessions.

Results: Fifty-four participants completed the simulation. Overall, 78% (n=42) of the participants failed (the measured SWPF value was less than 500) at least one of the three sessions of chest compressions. The median value and interquartile range of the SWPF was 4,304 (685–16,191). There were no reports of slipping down of the respirator or mechanical failure during chest compressions.

Conclusions: Although the median SWPF value was high during chest compressions, the tight-fitting PAPR did not provide adequate protection.

Keywords: powered air-purifying respirators, aerosol-generating procedures, chest compression.

Abbreviations: Coronavirus disease 2019, COVID-19; severe acute respiratory syndrome coronavirus 2, SARS-CoV-2; aerosol-generating procedure, AGP; personal protective equipment, PPE; cardiopulmonary resuscitation, CPR; National Institute for Occupational Safety and Health, NIOSH; powered air-purifying respirator, PAPR; health care worker, HCW; assigned protection factor, APF; fit factor, FF; simulated workplace protection factor, SWPF; interquartile ranges, IQR.

1. Introduction

The novel coronavirus disease 2019 (COVID-19) is a disease caused by the novel severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) virus which appeared in December 2019 and is now a worldwide pandemic.[1] For healthcare workers (HCWs) performing aerosol-generating procedures (AGPs) on patients with infectious diseases such as COVID-19, airborne personal protective equipment (PPE) and precautions are required.

Chest compressions are one of the main components of cardiopulmonary resuscitation (CPR) and are an AGP.[2] Although the evidence is limited regarding whether chest compressions put HCWs at risk of transmission of acute respiratory infections, aerosols can be generated during CPR by intubation, suctioning of body fluids, and manual ventilation.[3] Therefore, a precautionary approach to airborne infections is appropriate during CPR. Chest compressions require intense and dynamic upper body movements; thus, it is possible that HCWs' masks could lose close contact with their face during chest compression, which could then create a gap in which air could flow.

The National Institute for Occupational Safety and Health (NIOSH)-certified N95 filtering facepiece respirators (N95 respirators) are recommended to protect against airborne droplets, based on the Centers for Disease Control and Prevention guidelines.[4]

However, previous studies have shown that N95 respirators did not provide adequate protection during chest compressions due to inappropriate fitting.[5, 6] According to the NIOSH regulations, powered air-purifying respirators (PAPRs) are specified for high-hazard procedures such as AGPs, although PAPRs have been mainly used for industrial purposes and are not certified as medical devices. PAPRs, which use a battery-powered fan to draw ambient air through a filter and direct the filtered air into the breathing zone, can offer high protective performance. A previous study reported that loose-fitting PAPRs provide sufficient respiratory protection and comfort during chest compressions.[7] However, no studies have investigated whether other types of PAPRs, such as tight-fitting PAPRs, provide and maintain a protective effect during chest compressions.

Here, we aimed to 1) investigate the protective effect of tight-fitting PAPRs during chest compressions and 2) to clarify the safe and suitable use of PAPRs in the care of patients with airborne infectious diseases.

2. Methods

2.1. Study design and setting

This was a simulation study conducted at a single center from February 2021 to March 2021. The study was performed in an isolated room located at the Nagoya University Hospital (Nagoya, Japan). The Institutional Review Board of the hospital approved the study and written informed consent was obtained from each participant.

2.2. Participant selection

The inclusion criteria were as follows: 1) HCWs who were employed at our institution; 2) HCWs who were 20 years of age or older; and 3) those certified for the delivery of basic life support or advanced cardiovascular life support by the American Heart Association or the Japanese Association for Acute Medicine. The exclusion criteria were as follows: HCWs with conditions that could cause harm to their health due to performing continuous chest compressions on a manikin, such as pregnancy, asthma, coronary heart disease, and musculoskeletal diseases.

2.3. Measurements

2.3.1. Preparation for simulation

At the beginning of the simulation, the investigators held a brief training session for the participants, which included providing instructions on the flow of the study (Fig. 1) and

practice using PAPRs. After the training session, all participants completed a brief questionnaire about their demographic information (age, sex, body weight, and height), specialty (doctor, nurse, and others), and years of clinical experience as HCWs.

2.3.2. The tight-fitting powered air-purifying respirator

The PAPR equipment used in this study consisted of a half-mask respirator (BL-321H) and a filter (BLA-62; KOKEN LTD, Japan) (Fig. 2). The battery-powered fan automatically runs when the wearer starts breathing. The air flow standard of the BL-321H PAPR set by the manufacturer was 138 L/min. This equipment was certified by the National Certification Standard, TP100. The PAPR includes a particle filter, PL3, to protect from particles. During the simulation, we used a rechargeable lithium battery (3.7 V) that lasted 3.5 h when fully charged. The participants were equipped with the PAPR and confirmed that there was no problem with the operation of the PAPR.

2.3.3. Assigned protection factor of tight-fitting PAPRs

The NIOSH has published and enforced the assigned protection factor (APF) for respiratory protective equipment. The APF is the workplace level of respiratory protection that a respirator or class of respirators is expected to provide to wearers. The APF for the tight-fitting PAPRs was 50.[8] The fit factor (FF) represents the concentration ratio in and out of the respirator, which is calculated as the number of ambient particles divided by

the number inside the respirator. The FF must exceed the APF by at least ten times in order for the fit to be deemed adequate.[8] Therefore, tight-fitting PAPRs were assumed to have a protective effect when the FF was above or equal to 500.

2.3.4. Simulated workplace protection factor measurement during chest compressions

We measured the simulated workplace protection factor (SWPF) during chest compressions. The SWPF is the concentration ratio of ambient particles and particles inside the PAPR mask; it is a value indicating the level of protection provided by a respirator when subjected to a simulated work environment. We used the Mask Fitting Tester, Model MT-05U (SIBATA Scientific Technology LTD, Japan) to measure the SWPF and a particle generator for the mask fitting tester (SIBATA Scientific Technology LTD, Japan) to generate sodium chloride aerosol in this simulation. The mask fitting tester is equipped with a sampling tube that is exposed to the atmosphere (measures ambient particles) and a second sampling tube that measures particles inside the respirator. We inserted the inlet of the sampling tube through the gap between the mask and cheek. The inlet was placed between the participant's mouth and the inner surface of the mask. The manufacturer of the Mask Fitting Tester recommends the method described above as a method of daily measuring the FF.

The participants performed continuous chest compressions without ventilation on a Resusci Anne manikin (Laerdal Medical, Stavanger, Norway) three times for 2 minutes each time, with a 4-minute break between each session. During the sessions, the SWPF was continuously recorded every second in real-time mode. Participants wore the PAPR until the end of the simulation and were not allowed to touch or adjust their mask. One investigator oversaw that an appropriate speed and depth of chest compressions were maintained and provided feedback to participants in real time.

2.3.5. PAPR survey

The PAPR survey had 10 questions which were answered on a 5-point scale. After completing the simulation, participants were asked about the degree of difficulty to don or doff PAPR, obstruction of vision, interruption of verbal communication, difficulty in breathing through the PAPR, anxiety, facial pain or skin irritation, interference with CPR capability, and expected availability in resuscitation.

2.4. Outcome measures

The primary outcome was the ratio of any failure of protection (SWPF < 500) during the chest compression sessions. The secondary outcomes were the measured SWPF value, device problems including slipping down of the respirator, or mechanical failures during chest compressions. We also asked the participants to report their experiences, such as

difficulty with working while wearing the respirator.

2.5. Data analyses

A priori sample size calculation was performed in terms of primary outcome achievement. To achieve a ratio of the FF of PAPR ≥ 500 of 99%, with 95% confidence interval within ± 5% according to Clopper-Pearson's interval, 54 participants were required. Standard descriptive statistics were used to present all data. Categorical variables are reported as absolute numbers and percentages, and continuous variables are reported as median values and interquartile ranges (IQRs) because the data were not normally distributed. Analyses were conducted using JMP version 9.0.2 (SAS Institute Inc., Cary, NC).

3. Results

3.1. Characteristics of the study subjects

Fifty-four participants were included in this study. **Table 1** shows the participant characteristics. Overall, the median age was 34 (IQR 27–41) years, 39% (n = 21) were female, and the median body mass index was 21.4 (IQR 20.0–24.1). Participants were employed as doctors (57%, n = 31), nurses (33%, n = 18), and others (9%, n = 5).

3.2. Outcomes

Primary and secondary outcomes are presented in **Table 2**. Overall, 78% (n=42) of the participants failed (SWPF < 500) at least one of the three sessions of chest compression. The ratio of the failure of protection (SWPF < 500) was 72% (n = 39), 56% (n = 30), and 46% (n = 25) in the first, second, and third sessions, respectively. The median values and IQRs of SWPF were 4,304 (685–16,191) overall, and 2,749 (409–9,275), 4,679 (773–20,173), and 6,291 (1,117–21,011) in the first, second, and third sessions, respectively. There were no cases of slipping down of the respirator or mechanical failure during chest compressions. The patterns of each participant's SWPF changes over time are shown in Supplemental Fig. 1.

Survey results about the tight-fitting PAPR are presented in Table 3. Few participants found that the tight-fitting PAPR was difficult to don (4%) and doff (0%).

Thirteen (24%) participants said they had difficulty communicating verbally, and 11 (20%) said they had difficulty listening when wearing the PAPR. However, the majority of participants (85%, n = 46) stated that it seemed possible to use a PAPR during actual resuscitation.

4. Discussion

PPE worn by HCWs is critical for reducing infection transmission in healthcare settings, especially during the COVID-19 pandemic. Airborne PPE and precautions are required when AGPs are being performed.

Previous simulation studies showed that the use of N95 respirators did not result in adequate protection due to inappropriate fit; the FF decreased to <100 in most participants during chest compression.[5, 6] Another previous simulation study showed that a loose-fitting PAPR provides sufficient protection, with an SWPF >250 in all participants during chest compressions.[7] Therefore, these studies have suggested that HCWs engaging in chest compressions for patients with airborne diseases could wear PAPR with hoods rather than N95 respirators.[6] On the other hand, other types of PAPRs, such as tight-fitting PAPRs, may be used in healthcare settings. To the best of our knowledge, no study has yet explored the protective effects of tight-fitting PAPRs during chest compression or CPR. Accordingly, we performed this study to assess the influence of movement during chest compression on the protective performance of tight-fitting PAPRs.

We found that tight-fitting PAPRs did not provide adequate protection during chest compressions; specifically, 73% (n = 32) of the participants failed (SWPF < 500) at

least one of the three chest compression sessions. The APF of the tight-fitting PAPRs (50) is higher than that of N95 respirators (10); that is, PAPRs are expected to offer a higher level of effective protection performance than N95 respirators. In fact, during the chest compression sessions with tight-fitting PAPRs, the median SWPF value was as high as 4,304. Nonetheless, the vigorous movement involved in chest compressions seems to loosen the seal between the mask and the face and create a gap in which air could flow in and interfere with adequate protection.

The ratio of the failure of protection was higher in the first session than in the third session (72% vs. 46%; $p = 0.006$), although we did not aim to compare the differences in SWPF between sessions and could not explain the cause. As a possible factor, the movement involved in chest compressions may have decreased due to fatigue in the latter session. However, to reduce the impact of such a factor, the investigator observed that an appropriate speed and depth of chest compressions were maintained and provided feedback to participants in real time. In addition, the participants were not allowed to adjust the mask to be in a better position. However, they may have voluntarily learned the postures and movements in which the seal between the mask and the face was less likely to loosen. Although there may be a learning effect, this does not reduce the failure rate to a clinically significant extent: the failure rate was 46% in the third session.

The protection performance provided by respirators is dependent on the filter's efficiency and seal quality, which is influenced by the shape of the sealing surface, the pressure generated by the tethering devices, the respiratory flow rate, and the wearer's movements.[9] The advantages of a tight-fitting PAPR over N95 respirators are the generation of positive pressure and respiratory flow. On the other hand, the facepiece of the BL-321H is heavier than the N95 respirator and has a shape that protrudes from the surface of the face. These features could be a disadvantage as they may be influenced by dynamic movement with the upper body leaning forward. In addition, the facepiece could be large for the face, since about 40% of the participants were female; although the BL-321H is a Japanese product and is expected to fit Japanese people's faces, and most of the participants had a standard body mass index.

A previous review article about Middle East respiratory syndrome (MERS) suggested that HCWs who perform CPR for MERS patients should wear Level C PPE (including loose-fitting PAPR) rather than Level D PPE (including an N95 equivalent mask).[10] Considering the results of the present study as well, it may be better to use a loose-fitting PAPR instead of a tight-fitting PAPR for CPR in patients with infectious diseases. However, tight-fitting PAPRs have advantages over loose-fitting PAPRs; they are fast to don/doff, lightweight, compact, and have no hoses or belt-mounted battery

packs, which contribute to ease of work. Because PAPRs require batteries to filter out contaminated air, malfunctioning machines, such as disconnection circuits, can be fatal. In the present study, there were no cases of device problems during chest compressions. Regarding loose-fitting PAPRs, a study reported that some HCWs who wore loose-fitting PAPRs with an external belt-mounted blower and full-face shield (hood) were infected after pathogen exposure due to disconnection of the circuit of the respirator during the outbreak of MERS-related coronavirus.[11] The BL-321H model has no hoses or belt-mounted battery packs, which reduces the risk of disconnection of the circuit.

The possible routes of infection may include not only respiratory invasion of aerosols contaminated with the virus, but also contamination during doffing of PPE and mucosal exposure to body fluids when unconsciously touching the face, mask, or goggles. Among these routes, contamination frequently occurs while doffing PPE.[12] Simple doffing is an advantage of the BL-321H model, as no participant responded that the tight-fitting PAPR was difficult to doff in the present survey.

With regard to medical care in real settings, it has been reported that HCWs who wore N95 respirators were infected after performing CPR during the MERS or severe acute respiratory syndrome outbreak.[3, 13] Although there are various possible transmission routes (as mentioned above), experiences from past outbreaks of highly

contagious diseases taught us that HCWs should be protected from airborne disease transmission when performing CPR. In our facility, we treated approximately 80 patients with severe COVID-19 pneumonia in the intensive care unit. Using the tight-fitting BL-321H PAPR, we performed AGPs such as intubation, extubation, and bronchoscopy in patients with COVID-19. None of the HCWs became infected with symptoms or experienced nosocomial spread after caring for the patients. However, we did not perform CPR, including chest compressions, for patients with laboratory-confirmed COVID-19. This might suggest that chest compressions may require particularly intense movement in comparison with other procedures.

As per the current international CPR guidelines, the American Heart Association issued an interim update to its guidance for CPR in patients with suspected or confirmed COVID-19 infection.[14] According to the updated AHA guidelines, HCWs should don PPE to guard against contact with both airborne and droplet particles before entering the room of a patient experiencing cardiac arrest. However, the guidelines do not mention specific types or levels of PPE. In the future, the COVID-19 countermeasure revision process, preparation, and application of PAPR for emergency situations such as CPR should be discussed. It should be noted that the PAPR devices are not available at all facilities. Since most HCWs are unfamiliar with PAPR use, they need to be trained

regularly to use them well in clinical settings.

As a measure of protection against infections other than respirators, the AHA recommended that healthcare facilities consider replacing manual chest compressions with mechanical CPR devices for patients who meet the height and weight criteria to minimize HCW participation in CPR. Several randomized trials reported no significant difference in survival among patients resuscitated with a mechanical chest compression device compared with manual CPR.[15-17] In particular settings where it may be difficult or dangerous to perform high-quality chest compressions (e.g., few rescuers, prolonged CPR, CPR during transport, CPR during cardiac catheterization[18]), these devices may be useful. CPR for patients with airborne diseases also applies to these conditions.

4.1. Limitations

This study comprised a relatively small number of subjects with non-randomized design, there were several limitations and biases that should be considered when generalizing the results. First, the simulation environment has inherent limitations. Therefore, the outcomes of the present study may differ from those in real-world settings. For example, we did not consider the effects of tasks other than chest compressions that may be involved in CPR, such as bag-valve ventilation, intubation, and defibrillation. Although the outcomes could be affected by other tasks, we only

focused on chest compression in the present study. Second, the participants performed continuous chest compressions based on the assumption that the patient had an advanced airway. However, in patients without an advanced airway, chest compressions are briefly paused every 30 compressions to provide ventilation. In addition, the participant performed a simulation without verbally counting the number of compressions. However, HCWs usually count the number of chest compressions aloud in real settings, which can loosen the fitting of the PAPR. Third, we only evaluated one PAPR model produced by a single company. This model has only one mask size and does not therefore consider individual face size. Therefore, our results cannot be generalized to other models.

5. Conclusions

Tight-fitting PAPRs did not provide adequate protection during chest compressions. The results of the present study indicate that the protective effect of tight-fitting PAPRs is affected by the dynamic movements of the body. Further studies must be conducted to revise the guidelines for the level of respiratory protection for HCWs during CPR in patients with airborne diseases. Further randomized trials are needed to determine the appropriate type or level of respiratory protective equipment during CPR.

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Variables	Toral (n=54)
Age, year	34 (27-41)
Sex	
Male	33 (61%)
Female	21 (39%)
BMI, kg/m^2	21.4 (20.0-24.1)
Specialty	
Doctor	31 (57%)
Nurse	18 (33%)
Others	5 (9%)
Clinical experience, year	
< 2	19 (35%)
2-5	2 (4%)
5-10	12 (22%)
10 ≤	21 (39%)

Table 1. Characteristics of the participants

Data are presented as median with interquartile range or n (%).

	Ratio of the any failure of protection	SWPF*
Overall	78%	4,304 (685-16,191)
First session	72%	2,749 (409-9,275)
Second session	56%	4,679 (773-20,173)
Third session	46%	6,291 (1,117-21,011)

Table 2. Primary and secondary outcomes

*Data are presented as median with interquartile range.

Abbreviations: SWPF, simulated workplace protecting factor.

Question	Scale*		
	1-2	3	4-5
1. Was it difficult to don?	44 (81)	8 (15)	2 (4)
2. Was it difficult to doff?	53 (98)	1 (2)	0
3. Did it obstruct your vision?	41 (76)	5 (9)	8 (15)
4. Was it difficult to breathe through PAPR?	43 (80)	2 (4)	9 (17)
5. Did it cause fear and anxiety?	45 (83)	6 (11)	3 (6)
6. Was it difficult to communicate verbally?	33 (61)	8 (15)	13 (24)
7. Did it led to difficulty listening?	37 (69)	6 (11)	11 (20)
8. Did it cause skin irritation?	46 (85)	5 (9)	3 (6)
9. Did it interfere with your ability to do chest compressions?†	45 (83)	3 (6)	5 (9)
10. Is it possible to use PAPR in actual resuscitation?	1 (2)	7 (13)	46 (85)

Table 3. Survey on tight-fitting PAPR

Data are presented n (%). Abbreviations: PAPR, powered air-purifying respirators.

*On a 5-point Likert scale, in which 1 = never, 2 = rarely, 3 = sometimes, 4 = most of the time, 5 = always.

†Including one participant who did not answer the question.

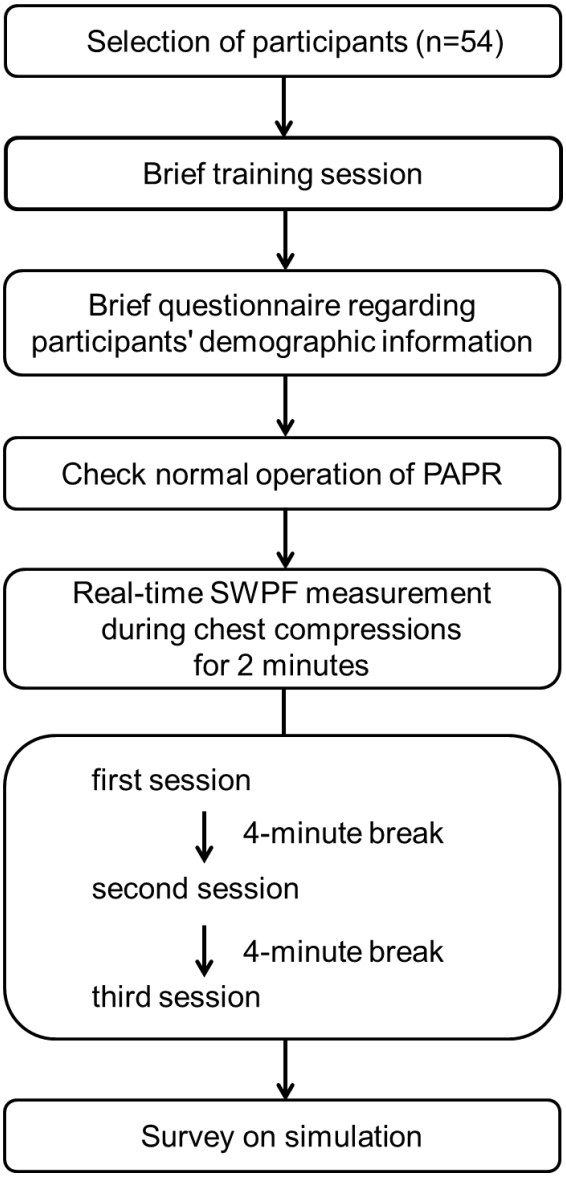
Figure legends

Figure 1. Study flowchart. PAPR, powered air-purifying respirator; SWPF, simulated workplace protection factor.

Figure 2. A tight-fitting PAPR; half-mask respirator (BL-321H) and filter (BLA-62).

Supplemental Figure 1. The pattern of each participant's SWPF changed over time. (A) First session; (B) second session; (C) third session. SWPF, simulated workplace protection factor.

Figure 1.


Selection of participants (n=54)
Brief training session
Brief questionnaire regarding participants' demographic information
Check normal operation of PAPR
Real-time SWPF measurement during chest compressions for 2 minutes
first session
4-minute break
second session
4-minute break
third session
Survey on simulation

Supplemental Figure 1.