Performance Evaluation of the Domestically Developed Powered Air Purify Respirator in Thailand

Kanit Tapasa*, Surisa Suriyoporn, Kansiree Kaewmorakot, Ekarat Meechoowas and Nuttawan Sawangboon

Division of Engineering Materials, Department of Science Service, Bangkok, 10400, Thailand

* Corresponding author. E-mail address: kanit@dss.go.th

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Abstract

The initial outbreak of COVID-19 in Thailand in 2020 revealed critical shortages in personal protective equipment (PPE), particularly Powered Air-Purifying Respirators (PAPRs), which are essential for protecting medical personnel from airborne pathogens. This study compared the performance of domestically manufactured PAPRs in Thailand (MM and PP) to two commercially imported models (TM and SM), both of which are generally recognized for their compliance with the EN 12941 standard. The study involved 20 subjects, comprised of 10 males and 10 females, to evaluate three key parameters: total inward leakage (TIL), air supply, and breathing resistance. To replicate real-world conditions, subjects wore ASTM-certified surgical masks beneath the PAPR during the TIL tests. The TIL test employed sodium chloride particles produced by an atomizer and was carried out in a sealed chamber. A scanning mobility particle sizer and laser photometer were used to monitor the concentrations of particles both within and outside the respirator. Leakage under dynamic situations was evaluated using standardized exercises following EN 12941 guidelines. Air supply and breathing resistance were tested with a Sheffield dummy head following international protocols. All PAPRs achieved %TIL values below the 1% EN 12941 threshold, with the TM model having the lowest leakage (0.097%). Domestically produced models performed similarly, with small variations in the PP model due to its PTFE membrane filter. Airflow rates exceeded the design specifications while breathing resistance remained within acceptable limits. Compared to a previous study utilizing dummy head testing, this research demonstrated improved consistency in %TIL results by employing human subjects, emphasizing the importance of real-world testing conditions. Furthermore, the present study highlights the potential of domestically manufactured PAPRs to serve as viable, cost-effective alternatives to imported models. Thai-manufactured PAPRs may improve national resilience in future public health emergencies while lowering reliance on global supply chains if they comply with rigorous testing requirements and demonstrate equivalent protective effectiveness.

Keywords: COVID-19, powered air purifying respirator (PAPR), total inward leakage (TIL), air supply, breathing resistance

Introduction

The COVID-19 pandemic, which began in early 2020, revealed a critical shortage of personal protective equipment (PPE) for medical personnel, including medical masks, protective suits, and powered air-purifying respirators (PAPRs). This shortage was exacerbated by severe disruptions in global supply chains, making the transportation and distribution of PPE exceedingly difficult. The pandemic exposed vulnerabilities in supply chains, which were previously optimized for cost efficiency but lacked resilience to such unprecedented disruptions (Knezevic et al., 2022). Respirators are essential for protecting healthcare workers (HCWs) from airborne pathogens, especially during pandemics and epidemics involving highly infectious agents such as SARS-CoV-2, SARS-CoV-1, MERS, and Ebola. The effectiveness of respirators depends on several factors, including design, material, proper fit, and environmental conditions (Young et al., 2022). HCWs are at particular risk due to their close contact with infected patients and the performance of medical procedures that generate aerosols (Scantling-Birch et al., 2021). Common types of respirators used in healthcare settings include filtering

facepiece respirators (FFRs) and PAPRs. Compared to FFRs such as N95 masks, PAPRs offer superior protection, comfort, and reusability, making them suitable for high-risk scenarios (Chughtai et al., 2020). By maintaining positive pressure and a continuous supply of clean air through battery-powered blowers, PAPRs provide enhanced safety for HCWs (Elkington et al., 2021; Munro et al., 2021).

Despite their advantages, PAPRs are often expensive, with costs being a barrier in some regions, prompting efforts to develop more cost-effective solutions (Deepu et al., 2022). During the COVID-19 pandemic, there was the development of low-cost, 3D-printable PAPRs, making these devices more accessible and affordable, especially in resource-limited settings. For instance, the Hygieia PAPR design met the National Institute for Occupational Safety and Health and Occupational Safety and Health Administration standards, providing a viable alternative when commercial options are unavailable (Nagel et al., 2021). Similarly, the PeRSo prototype, developed to minimize manufacturing complexity, has been preferred by HCWs for its comfort and effectiveness, reducing the need for frequent PPE changes and improving patient communication (Elkington et al., 2021) (Munro et al., 2021). The PanFab team's open-source PAPR designs have also been validated for safety and performance, offering modular components that can be locally manufactured, thus addressing supply chain disruptions (Kothakonda et al., 2021). In rural settings, innovative approaches such as converting surgical helmets into emergency PAPRs have been employed, demonstrating efficacy against a range of aerosol sizes (Kessel et al., 2022). However, these designs often lack rigorous evaluation against international standards like EN 12941, limiting their adoption in clinical settings.

In Thailand, the COVID-19 pandemic highlighted the country's heavy reliance on imported PPE, including PAPRs, due to limited domestic manufacturing and testing capabilities. The inability to procure sufficient PAPRs for HCWs during the outbreak prompted a collaborative effort to develop locally produced PAPRs. Leveraging available materials and manufacturing capabilities, the objective of these initiatives was to enhance frontline HCW safety and reduce reliance on foreign supply chains. A notable example is the PAPR design by Techakittiroj et al. (2021), which utilized a customized HEPA H14-class filter, capturing 99.995% of 0.3-micron particles. It also included a pre-filter for larger particles and a Delta Electronics Model# BFB1012EH-A centrifugal fan to maintain airflow. This locally sourced and quickly implemented solution addressed the urgent need for PAPRs and demonstrated its effectiveness through the distribution of 500 units. Other efforts, such as the Honda Thailand Foundation (2021) produced and donated 1,000 negative and positive pressure masks. The Electricity Generating Authority of Thailand (2021) developed a protective hood specifically designed for medical personnel. Khon Kaen University (2021) collaborated to create the PAPR Suit for healthcare workers treating COVID-19 patients. Additionally, Salika (2020) reported on the P-Mask, a reusable face mask developed by Thai innovators to address the PPE shortage. These innovations addressed immediate demands but lacked comprehensive evaluation, particularly human testing aligned with EN 12491 standards. Further systematic evaluation and development, including rigorous testing, remain essential for these devices to meet international standards. Building on this foundation, our recent study (Suriyoporn et al., 2023) emphasized the effectiveness of domestically manufactured PAPRs during the pandemic. The findings demonstrated significant potential for local innovations to align with international standards while addressing specific limitations, such as airflow stability and filter performance. These results provided valuable insights that informed the current research, enabling more rigorous evaluations and broader comparisons with commercial models.

Recognizing this challenge, the Department of Science Service (DSS), Thailand, established a testing facility compliant with the EN 12941 standard to evaluate three critical parameters of PAPR performance: Total Inward Leakage (TIL), which measures the PAPR's ability to prevent airborne contaminants from leaking into the wearer's breathing zone; Air Supply: which assesses the adequacy of the PAPR's airflow to ensure sufficient ventilation and prevent respiratory distress; and Breathing Resistance, which evaluates the ease of inhalation and exhalation through to ensure the PAPR does not cause undue physical strain on the wearer. This facility represents a significant achievement, enabling the systematic evaluation of PAPRs, and ensuring compliance with international safety requirements. This not only helps to ensure the quality of locally made PAPRs but also improves national readiness for future public health emergencies. This facility is a noteworthy accomplishment, allowing for the systematic evaluation of PAPRs while maintaining conformity with international safety standards. This not only contributes to the quality of locally produced PAPRs but also increases national preparedness for future public health emergencies.

This research, approved by the Human Research Ethics Committee of Saraburi Hospital under ethical certificate number EC026/2567, builds on DSS's groundwork. Two domestically manufactured PAPRs (MM and PP) were systematically evaluated against two commercial models (TM and SM). Using rigorous methods, including gender-balanced testing groups, a scanning mobility particle sizer (SMPS), and the additional study on Sheffield dummy head, the study assesses TIL, air supply, and breathing resistance under standardized conditions. The findings provide a cost-effective alternative to imported PAPRs while reinforcing DSS's testing capabilities as part of Thailand's comprehensive public health strategy.

Materials and Methods

Samples and specifications

Four Power Air-Purifying Respirators (PAPRs) presented in Fig. 1 were evaluated, including two domestically manufactured models (MM and PP) and two commercially imported ones (TM and SN). The commercial PAPRs, both FDA-approved, are widely recognized for compliance with EN 12941. Specifically, the commercial models included the Tecmen Freflow V1 TM-H2 (TM), manufactured by TECMEN Electronics Co., Ltd., China, and the Shine P-SH100 (SN), produced by Changzhou Shine Science & Technology Co., Ltd., China. The domestically manufactured PAPRs consisted of the Menam Mechanika PAPRs SC-003 (MM), developed by Menam Mechanika Co., Ltd., Thailand, and the PRIMA P-PAPR PLT202101 (PP), manufactured by Prima Laser Therapy Co., Ltd., Thailand. The domestically manufactured PAPRs were designed with HEPA or PTFE membrane filters. The objective of these devices was to balance affordability with performance. Comparisons focused on key parameters: Total Inward Leakage (TIL), air supply, and breathing resistance. The technical specifications for all PAPRs, including air supply rates, filtering efficiency, and operational times, are listed in Table 1. Manufacturer data served as the basis for the parameters, which were independently verified throughout the investigation.

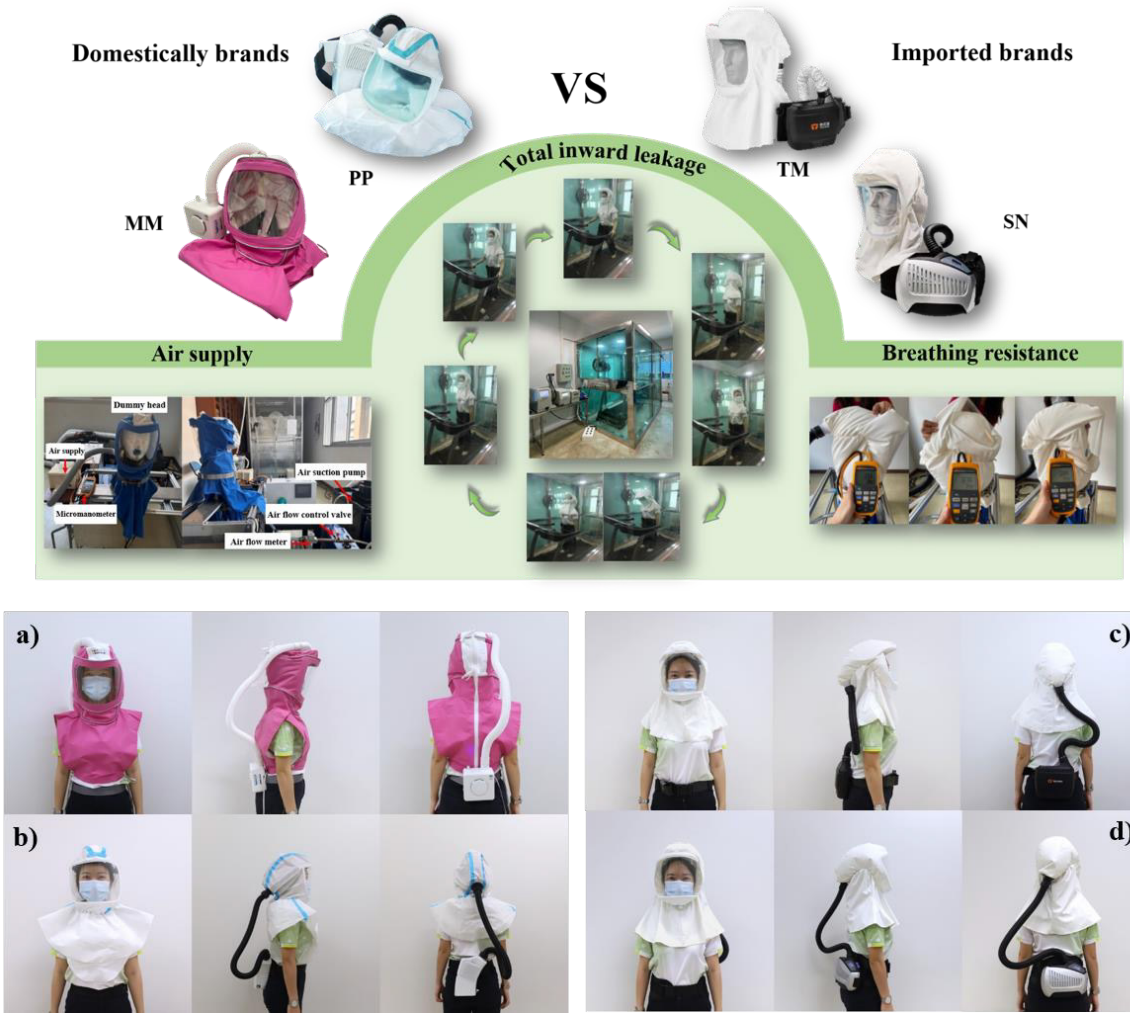

Figure 1 Four Powered Air-Purifying Respirators (PAPRs) were evaluated in this study: a) MM, b) PP, c) TM, and d) SN. The domestically manufactured models (MM and PP) were designed with HEPA or PTFE membrane filters, prioritizing affordability and performance, while the commercially imported models (TM and SN) are FDA-approved and compliant with EN 12941. The evaluations focused on Total Inward Leakage (TIL), air supply, and breathing resistance to assess their protective effectiveness and user comfort

Table 1 Specification of PAPR samples

Parameters/Properties	MM	PP	TM	SN
Brand/Manufacturer	Menam Mechanika	Prima	Tecmen	Shine
Model	PAPRs SC-003	PFT20210001	Freflow V1 TM-H2	P-SH100
Air flow rate (l/min)	170 - 340	123 - 240	170 - 210	170 - 230
Working time (hr)	7	8	9	>10
Filtering Efficiency (%)	>99.99 (0.3 μm)	99 (0.5 μm) 96.7 (0.1 μm)	>99.99 (0.3 μm)	>99.99 (0.185 μm)
Filter type	HEPA filter	PTFE membrane	HEPA filter	HEPA filter
Weight (kg)	2.00	1.60	1.02	1.37

Total Inward Leakage (TIL)

The TIL test is essential to ensure the PAPR's efficacy in providing respiratory protection by preventing the ingress of unfiltered air. TIL was calculated as the ratio of particle concentration inside the respirator to the

outside environment, expressed as a percentage. The Protection Factor (PF) of a respirator, which is the ratio of the concentration of an airborne contaminant outside the respirator to the concentration inside, is a critical measure of its effectiveness. For instance, studies have shown that air-purifying respirators such as half-face masks offer PFs of 14, full-face masks offer PFs of 112, and PAPRs showed PFs of 1328, for 0.28-0.3 μm size standard sodium chloride (NaCl) aerosols (Ganesh et al., 2019). High PF indicates minimal inward leakage.

The study of the TIL of PAPRs is crucial for understanding their effectiveness in protecting users from hazardous aerosols. TIL measures the amount of contaminant that penetrates the respirator, combining leakage through the face seal and filter penetration. Various studies have explored different aspects of TIL in PAPRs. For instance, Sekoguchi et al. (2022) evaluated the performance of PAPRs under non-recommended wearing methods and found that PAPRs maintained low leakage rates (0.18-0.42%) compared to replaceable particulate respirators (RPRs), which had higher leakage rates (1.82-10.92%) when worn incorrectly. This suggests that PAPRs are more robust against improper usage. Similarly, Borodina et al. (2020) conducted experimental studies to determine the protection factor of filter respirators with forced air supply, finding that the average protection factor ranged from 99.93 to 99.97, meeting the stringent requirements of EN 12941: 2004. Koh et al. (2011) used local flow measurement techniques and fog flow visualization to assess the inward leakage of two tight-fitting PAPRs, noting minor leakage at the beginning of inhalation, likely through exhalation valves, but not enough to compromise protection significantly. Additionally, Rengasamy et al. (2018) and Rengasamy et al. (2021) highlighted the importance of standardized testing methods, such as those specified by ISO 16900-1:2014, which use NaCl and corn oil aerosols to measure TIL, ensuring consistent and reliable results across different studies. Nicas (2023) discussed historical TIL studies, emphasizing the need to correct respiratory tract deposition to avoid underestimating TIL values, a consideration that remains relevant for modern PAPR evaluations. Zhuang et al. (2015) investigated the variability in TIL measurements across different anthropometric panels, finding that while variability exists, it is relatively small and can be mitigated by using facial dimension-based fit test panels.

TIL Testing procedure

The TIL testing was conducted in a sealed chamber designed in compliance with EN 12941 to ensure controlled and standardized conditions. The chamber was equipped with a treadmill, a supplementary fan with a 350 mm diameter for air circulation, and particle-measuring probes. Sodium chloride particles, ranging in size from 0.02 to 2 μm, were generated using a 2% NaCl solution with an atomizer (TOPAS model ATM230), (Topas GmbH, 2021). These polydisperse, dried particles were diluted with HEPA-filtered air and introduced into the chamber at a flow rate of 100 L/min through a top-mounted duct and distributor, which directed the aerosol downward over the test subject's head. The supplementary fan ensured thorough mixing of the aerosol within the chamber. To replicate typical environmental conditions, the airflow velocity near the subject's head was maintained at 2 m/s when the fan was operational. With the fan turned off and the subject standing still at the center of the treadmill, the background air velocity within the chamber was measured between 0.12 and 0.2 m/s. Additionally, the relative humidity inside the chamber was kept below 60% to further simulate controlled environmental conditions (European Committee for Standardization, 2023). To measure TIL, a scanning mobility particle sizer (SMPS, model 3938L89, TSI Inc. (USA)) and laser photometer (LP, model 8587A, TSI Inc., USA) were used to determine particle concentrations upstream (outside the respirator) and downstream (inside the respirator). A schematic diagram of the chamber and experimental setup is provided in Fig. 2 (a).

Twenty volunteers, evenly divided by gender, participated in the TIL test conducted according to the EN 12941 standard. Prior to testing, all participants provided health check certificates and completed a safety and health checklist to confirm their suitability. During the testing, their oxygen levels and blood pressure were closely monitored to ensure safety. To simulate real-world conditions in high-risk aerosol contamination environments, such as healthcare settings, participants wore surgical facemasks (Type II, ASTM-certified, 3-ply, manufactured by Double A (1991) Public Company Limited, Thailand) beneath the PAPR. These facemasks added a layer of protection during donning and doffing procedures. However, it may introduce variables that slightly alter the measured performance of TIL. The testing began by setting the PAPR's flow rate to the manufacturer's minimum design flow rate. Participants were placed in the test chamber, with the testing sequence starting with female subjects followed by male subjects, and the sampling probe was connected. To establish the baseline, participants walked on a treadmill at 6 km/hr for 2 min while measurements of the test substance concentration inside the facepiece were taken. During the walk, participants performed a series of exercises designed to simulate realistic use scenarios (see Fig. 2 (b)):

a) Walking without head movement or talking for 2 min.

b) Turning the head from side to side (approximately 15 times) over 2 min, simulating scenarios such as inspecting the walls of a tunnel or scanning a confined space.

c) Moving the head up and down (approximately 15 times) over 2 min, mimicking actions such as inspecting ceilings, overhead structures, or objects positioned on the ground.

d) Reciting the alphabet or an agreed text aloud for 2 min, simulating communication with colleagues.

e) Walking without head movement or talking for 2 min.

Exercises b), c), and e) were conducted with a supplementary fan generating an air velocity of 2 m/s, directed alternately at the front, side, and rear of the respirator. During the final 100 seconds of each exercise, the concentration of NaCl particles was measured both upstream (outside the facepiece) and downstream (inside the facepiece). The percentage of Total Inward Leakage (%TIL) was calculated using the formula:

$$\%\text{TIL} = 1.25 \times [C2 / C1] \times 100$$

where C2 represents the concentration of NaCl particles downstream (inside the facepiece), and C1 represents the concentration upstream (outside).

Each test was repeated three times per participant, and the overall average %TIL and standard deviation were calculated for each subject. Finally, the overall average %TIL and standard deviation for all respirator samples were determined. Statistical comparisons were performed to analyze the results further.

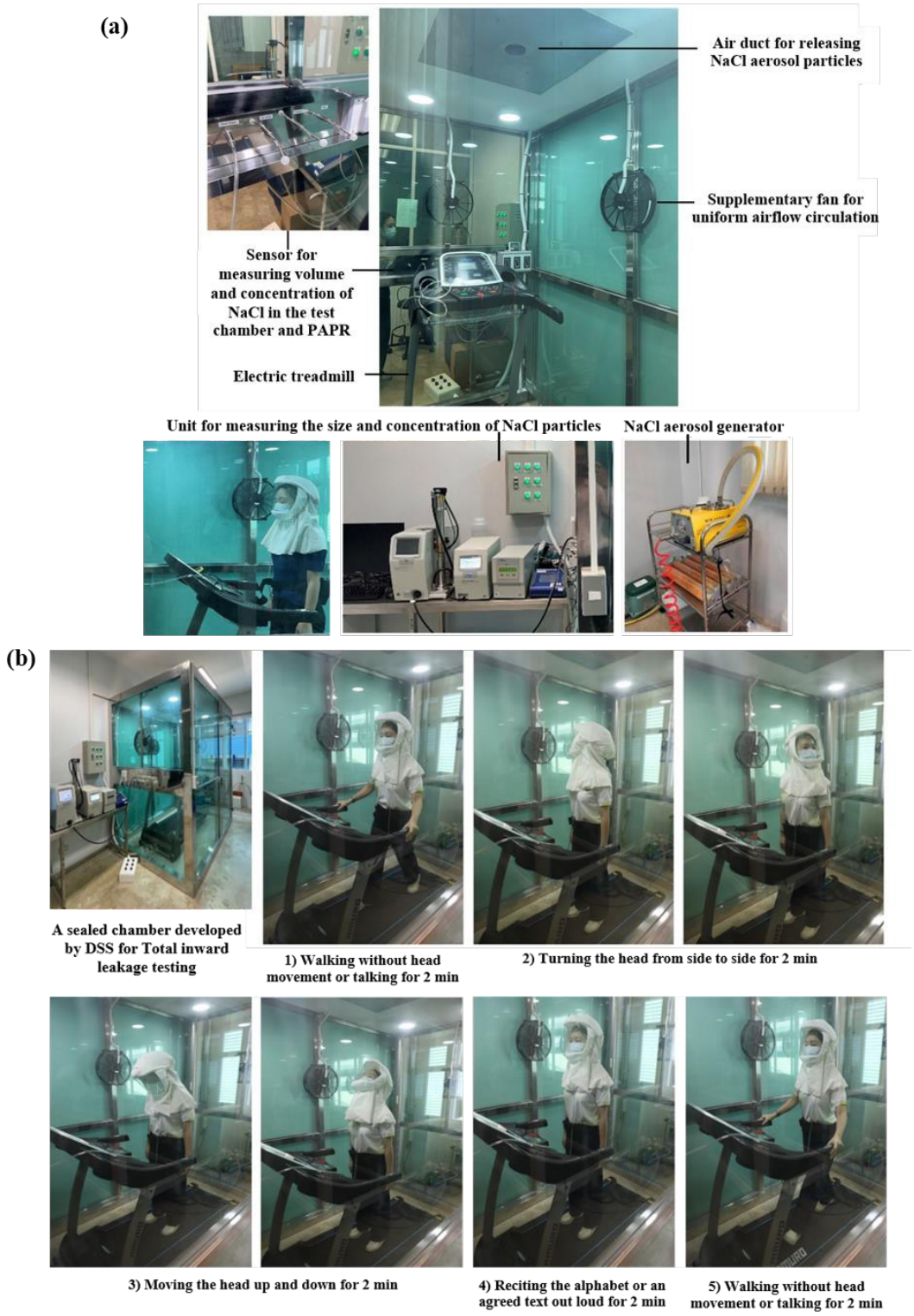

Figure 2 (a) The total inward leakage (TIL) test chamber used for evaluating particle leakage into the PAPR. The chamber is equipped with essential components, including an air duct for releasing NaCl aerosol particles, a supplementary fan for uniform airflow circulation, and a sensor for measuring the volume and concentration of NaCl particles inside the chamber and the PAPR. (b) The exercises of the test subject were performed in the TIL test chamber. The subject performed a sequence of standardized activities on a treadmill inside the sealed chamber. The experimental setup and specific exercises conducted during the TIL test are illustrated in steps (1) to (5)

Air Supply and Breathing Resistance testing procedure

Airflow and breathing resistance were evaluated using a Sheffield dummy head developed by DSS (as shown in Fig. 3) and testing equipment designed in compliance with the EN 12941 standard (European Committee for Standardization, 2023). The objective of the testing was to ensure that PAPR systems delivered air at or above the manufacturer's specified minimum design flow rate for a continuous duration of at least 4 hr. The positive pressure within the helmet or hood, maintained by the PAPR system, was monitored to ensure it did not exceed 5 mbar, as required by the standard. The Sheffield dummy head was equipped with sensors to measure airflow rates during both inhalation and exhalation, replicating human respiratory patterns. Airflow stability was assessed to confirm consistent performance over the testing period. Breathing resistance was measured under standardized conditions to evaluate the ease of breathing while wearing the PAPR, ensuring minimal physical strain on the user.

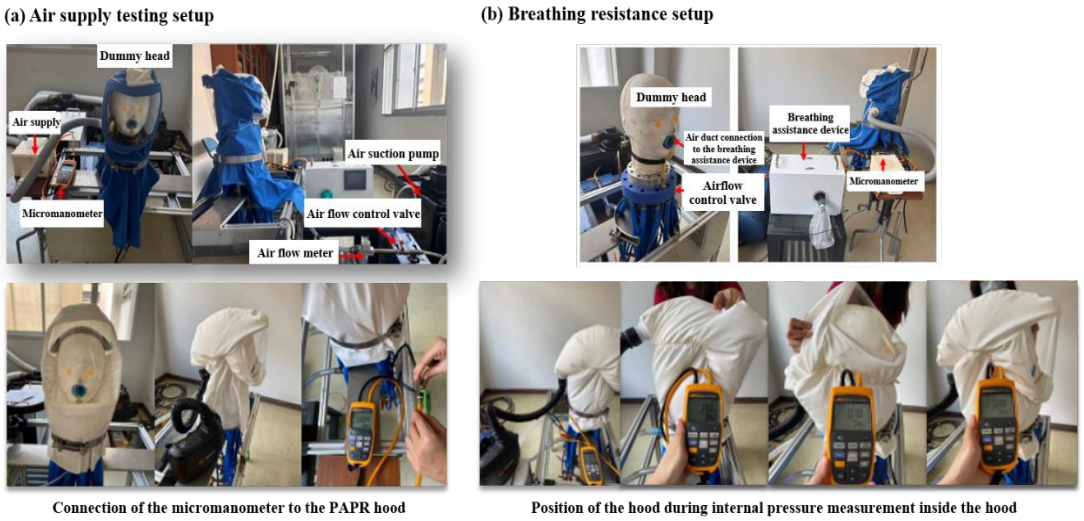

Figure 3 Experimental setup developed by the Department of Science Service for (a) air supply and (b) breathing resistance testing. The setup includes key components such as the dummy head for simulating the human respiratory system, air supply systems, and micromanometers to measure airflow and pressure changes. Airflow was measured using an airflow meter and control valve to ensure consistent conditions. The breathing resistance test utilized a breathing assistance device connected to the PAPR hood via an air duct, with internal pressure readings recorded using the micromanometer

Results

The sodium chloride particles generated by the atomizer within the chamber were polydisperse, with a size distribution ranging between 0.01 and 1 μm as specified in the manufacturer's certificate (TOPAS ATM230, Manufacturer Certificate), (Topas GmbH, 2021). The average particle size recorded during the test was approximately 0.1 μm. These generated particles are notably smaller than the typical size of the COVID-19 virus, which ranges between 0.05 to 0.14 μm (Cuffari, 2020), ensuring that the test particles provided a rigorous challenge for the PAPRs. Fig. 4 summarizes the %TIL results for all test subjects, presenting the overall average %TIL and standard deviation for each respirator sample tested. The results demonstrate that all %TIL values measured during this study were below the 1% threshold established by the EN 12941 standard. This indicates that all PAPR samples effectively protected the wearers from the penetration of these small particles, including those within the size range of the COVID-19 virus.

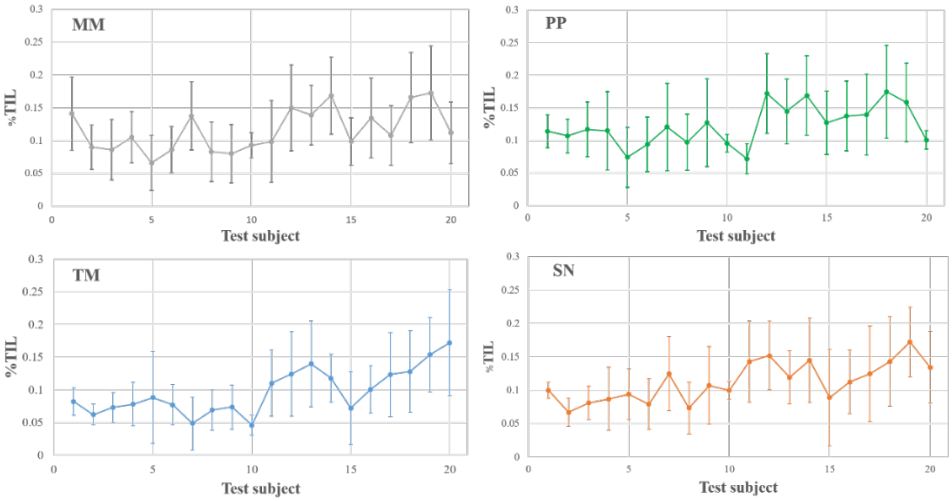

Figure 4 Results of %TIL for all test subjects The graph illustrates individual %TIL values for each of the four tested PAPR models (MM, PP, TM, and SN) across 20 participants

Fig. 5 presents a boxplot comparing the %TIL values for the four PAPR brands tested by 20 subjects. The whiskers in the boxplot indicate the range of the data, excluding outliers, while the notches in each box indicate the median %TIL value. The boxplot provides a visual representation of the %TIL distribution for each PAPR brand. The notch in the box represents the median %TIL value. As evident from the plot, all tested PAPR exhibited %TIL values below 0.2%, significantly lower than the EN standard's maximum inward leakage limit of 1%. A closer look at the results reveals that the TM PAPR had the lowest %TIL value (0.097%), followed by the PP (0.123%). Statistical analysis using one-way ANOVA revealed no significant difference in average %TIL among the four brands ($p = 0.078$), indicating that all PAPRs provided effective protection against small particles, including those within the COVID-19 virus size range (approximately 50-140 nanometers in diameter). However, analysis of the averaged %TIL values revealed a statistically significant difference between male and female test groups at the 95% confidence level. The male group had a higher average %TIL than the female group. This discrepancy may be attributed to the testing sequence, as all male testers followed the female testers, potentially leading to partial clogging of the PAPR filters. The study did not investigate physiological factors contributing to this variation, so no conclusions can be drawn about gender-related differences in %TIL.

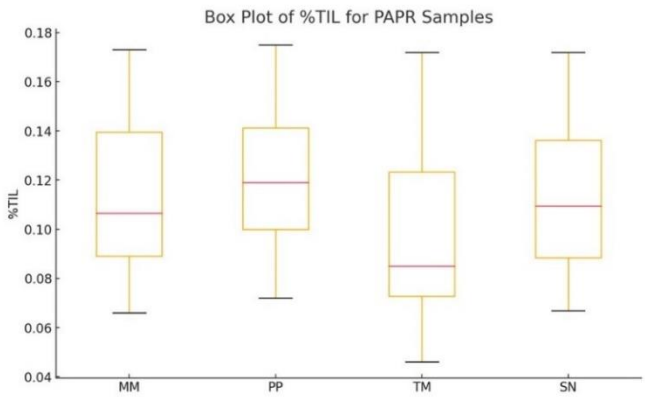

Figure 5 Averaged %TIL of all PAPR samples The boxes represent the interquartile range (IQR), with the red line indicating the median %TIL value for each model

Table 2 presents the averaged breathing resistance (mbar) and airflow rate (L/min) for all PAPR samples, measured using the Sheffield dummy head both before and after the TIL test. Each PAPR maintained a consistent airflow rate and low breathing resistance over the 4-hour testing period, meeting EN 12941 requirements. After the TIL test, minor decreases in airflow rate were observed for most samples. Notably, the PP sample showed the most significant percentage decrease in airflow (-12.39%), while SN (-5.58%), MM (-2.15%), and TM (-0.96%) samples exhibited smaller changes. These results align with prior findings (Suriyoporn et al., 2023), further validating the reliability of domestically manufactured PAPRs. The airflow and breathing resistance outcomes from the current study reflect improved performance, particularly for the PP model, which exhibited notable enhancements in airflow stability compared to earlier evaluations. These findings suggest that the PP sample may have experienced filter clogging or reduced blower efficiency during the test, warranting further investigation to determine the root cause of this performance decline.

Table 2 Results of breathing resistance and air supply of all PAPR samples before and after the TIL test

PAPR Samples	Averaged breathing resistance (mbar)	Averaged air flow rate (liter/min)		
		Before TIL test	After TIL test	% Change
MM	0.16	155.72	153.57	-2.15
PP	0.74	123.90	111.51	-12.39
TM	0.74	177.60	176.64	-0.96
SN	0.16	165.81	160.23	-5.58

Discussion

The research showed that all of the PAPRs that were tested effectively protected people from airborne contaminants, with %TIL values well below the 1% threshold required by the EN 12941 standard. The observed %TIL range is comparable with earlier study findings, such as Borodina et al. (Borodina et al., 2020), who reported consistent %TIL values below 1% for PAPRs with forced air supply, and Sekoguchi et al. (Sekoguchi et al., 2022), who discovered low leakage rates (0.18%-0.42%) under varied testing conditions. These comparisons demonstrate the effectiveness of PAPRs in reducing inward leakage. The domestically developed models (PP and MM) performed comparably to commercial models (TM and SN), with the TM model having the lowest %TIL value (0.097%). The slightly higher %TIL values seen in the PP and MM models may be due to changes in technical parameters. The PP sample, for example, had a PTFE membrane filter, which may be more susceptible to surface pore blockage during extended usage than the HEPA filters used in commercial devices. This is consistent with the findings of Rengasamy et al. (2018), who highlighted the role of filter material in determining PAPR performance. Despite these variances, all models met EN 12941 standards, demonstrating the potential of domestically produced PAPRs as cost-effective alternatives.

Compared with findings from our previous study (Suriyoporn et al., 2023), the %TIL values for domestically manufactured PAPRs in this study demonstrated improved consistency. The MM and PP models showed lower variability in %TIL results compared to prior evaluations, highlighting advancements in manufacturing quality and filter design. The previous study relied on testing with a dummy head, which is useful for preliminary assessments but does not accurately represent real-world conditions involving human factors such as facial dimensions and fit variability. On the other hand, the current study included human subjects allowing for a more

comprehensive evaluation of PAPR performance under practical use scenarios. Additionally, the improved performance of domestic models, particularly the MM and PP, reflects advancements in filter material design and manufacturing processes.

The study displayed several strengths, including an extensive evaluation of PAPR performance using thorough EN 12941-compliant methods, gender-balanced participant sampling to account for anthropometric variability, and simulation of real-world conditions using ASTM-certified surgical facemasks. These strengths contribute to the findings' robustness and application. However, certain flaws were identified. The large decrease in airflow rate for the PP model (-12.39%) indicates a potential reliability issue, most likely owing to filter blockage or reduced blower efficiency, that requires further investigation. Additionally, the gender differences in %TIL results indicate that the testing sequence, with male individuals coming after female participants, may have impacted results due to partial filter blockage. Physiological factors that could contribute to this variance were not investigated, which limits the interpretation of gender-related differences. The comparison between the current and previous studies by Suriyoporn et al. (2023) reveals similarities and differences in performance metrics. Both studies confirm the effectiveness of the domestically manufactured PAPRs in meeting international safety standards. However, the current study highlights greater airflow stability and improved filtration efficiency in the MM and PP models, demonstrating advancements over the previous evaluations. These improvements suggest that insights from earlier work, such as addressing filter clogging issues and enhancing blower design, were successfully integrated into the latest designs.

Key technological differences between the domestically developed and commercial PAPRs are likely to have contributed to performance variations. Both commercial models employed HEPA filters with superior clogging resistance, whereas the domestic model (PP) used PTFE membranes for cost efficiency. The commercial models may have slightly superior performance due to improved durability and airflow stability. These findings are similar to previous research, including that of Nagel et al. (2021) and Elkington et al. (2021), which emphasize the importance of local innovation and trade-offs in cost-effective PPE development. The domestic models' dependence on local materials and simplified designs demonstrates a promising pathway for resource-limited settings, but further improvements are needed to match the long-term performance of imported models. To find ways around these limitations, future research should focus on optimizing filter materials, such as making the transition from PTFE membranes to HEPA-grade filters, as well as improving blower design to ensure consistent airflow over extended use. Randomizing the testing sequence and including pre- and post-test filtration efficiency measures would improve the dependability of future evaluations. Furthermore, direct comparisons under extended-use situations may provide further insight into the long-term performance of domestic and commercial PAPRs.

The study's broader implications highlight the potential for domestically built PAPRs to reduce reliance on imported models while maintaining international standards. The establishment of a national testing facility by the Department of Science Service (DSS) has been pivotal in enabling these evaluations, driving innovation, and strengthening Thailand's preparedness for future public health emergencies. Findings from both this and the previous study reinforce the potential for domestically developed PAPRs to align with global safety standards, reducing reliance on imports and providing cost-effective solutions for resource-limited settings. By addressing identified weaknesses and continuing to align domestic solutions with global safety benchmarks, Thailand can further bolster its resilience and capacity to respond effectively to crises. Additionally, this study adds insightful

information to the international discussion on PAPR performance, encouraging further innovation and progress in the development of high-quality personal protective equipment (PPE).

Conclusions and Suggestions

This study evaluated the performance of two domestically manufactured PAPR devices in Thailand, with a research protocol involving human subjects received approval from the Human Research Ethics Committee of Saraburi Hospital (Ethical Certificate Number: EC026/2567). The investigation primarily focused on inward leakage (%TIL), user comfort during extended use, and compliance with international safety standards. The results showed that the %TIL for all tested PAPR devices remained below 0.2%, significantly lower than the 1% threshold mandated by the EN 12941 standard. Statistical analysis using one-way ANOVA revealed no significant differences in average %TIL among the four brands tested. This indicates that all PAPRs provided effective protection against small particles, including those in the size range of the COVID-19 virus (approximately 50-140 nanometers in diameter). Furthermore, all PAPR samples maintained internal hood pressure below 5 mbar and consistent airflow delivery exceeding 4 hours, ensuring both protection and comfort for users in high-risk environments. Additionally, the low breathing resistance and stable airflow delivery contribute to their usability for prolonged periods.

This research builds upon the groundwork established by our previous investigation, which provided foundational insights into the performance of domestically manufactured PAPRs. The findings from both studies highlight consistent progress in addressing technical limitations, improving filter design, and advancing the reliability of Thai-produced PAPRs. Together, they reinforce the potential for local innovations to align with international safety standards while reducing dependency on imported equipment. These findings demonstrate that domestically produced Thai PAPRs effectively meet international safety standards. They also offer reliable protection against airborne particulate matter, including viruses like COVID-19. The successful development and evaluation of these devices reflect Thailand's growing expertise in personal protective equipment (PPE) production. This achievement exemplifies Thailand's dedication to safeguarding its healthcare workforce and ensuring public health security during critical situations. The combined implications of these studies emphasize the importance of continued innovation and investment in local PPE manufacturing, which can bolster national preparedness and resilience in future public health crises.

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Author Contributions

Author 1 (Kanit Tapasa) : Conceptualization, Development or design of methodology, Data analysis and interpretation, Manuscript writing.

Author 2 (Surisa Suriyoporn) and 3 (Kansiree kaewmorakot) : Request for Ethics in Human Research, Volunteer Recruitment, Investigation, Collection of data.

Author 3 (Ekarat Meechoowas) : Project Coordination and Facilitation.

Author 4 (Nuttawan Sawangboon) : Manuscript review and editing.

Conflict of Interests

All authors declare that they have no conflicts of interest.

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