Comfort evaluation of a dynamic protective airflow system using human test subjects

Kim Hagström [a], *Ismo* Grönvall [a], *Petri* Kalliomäki [b], *Henna* Maula [b], *Arttu* Sivula [b]

[a] Halton Technology, Halton Oy, Kausala, Finland, firstname.surname@halton.com.

[b] Research group for Built Environment, Turku University of Applied Sciences, Turku, Finland, surname.firstname@tuamk.fi.

Abstract. Amount of sick leave days among nurses is in relatively high level compared to many other occupations. One of the risk factors for nurses at work are respiratory infections.
According to recent studies, there is a high risk for nurses to be exposed to microbes exhaled by patients especially, while they are conducting their work close to patient.
Current ventilation solutions that are used in patient environments are not designed to address this challenge. At best, they are able to dilute the microbial concentrations in the room, but they are not able to affect the nurse's exposure to patients' outbreath close to patients. These may lead to substantially higher exposure levels compared to room air conditions.
To reduce HCW's and especially nurses' exposure and infection risk, a new dynamic protective flow ventilation approach has been developed for patient environments (isolation rooms, intensive care and standard patient rooms). In previous studies, the efficiency of protective flow ventilation as well as thermal comfort has been verified by using breathing thermal manikin and tracer gas experiments.
In this laboratory study done in a simulated patient room, the thermal comfort provided by the protective ventilation solution is studied with human subject experiments. The participants are exposed to indoor environment, both in stable conditions and in a dynamic situation in which patient / nurse interaction is simulated. The thermal comfort is evaluated primarily by questionnaires, which the subjects will complete in different stages of the experiment. Physical measurements are conducted in parallel.
The presentation will outline previous development stages and will especially focus on presenting the results of human subject experiment.

Keywords. HCW, HAI, Infection, Ventilation, Protective airflow, Exposure
DOI: https://doi.org/10.34641/clima.2022.87

1. Introduction

Healthcare workers (HCW) and especially hospital nurses, who are constantly in contact with patients and visitors while treating patients are exposed to multiple occupational health risks in their work. Nurses are exposed to healthcare-associated infections and transmission of highly infectious diseases from infected patient to other patients and HAIs occurs constantly in hospitals and healthcare centres. This challenge has been especially emhasized in relation to certain infective diceases such as tubeculosis and small-box and more recently related to pandemic outbreaks. It has also been acknowledged that some high risk treatment procedures such as suction and incubation pose an incereased risk for infection transmission.

If a patient has or is suspected to have an infectious disease, the patient may be transferred to an infection isolation room that is especially built for such treatment and together with personal protective equipment (PPE) the exposure to and spreading of the infection can be reduced.

However, vast majority of close proximity patient contacts take place during "normal" treatment work in wards. In a pandemic situation personal protection precautions are emphasized and introduced also in wards as infectious patients have to be located there as well due to lack of isolation rooms. But this is a special condition and it may not be realistic to assume PPE's to be used constantly by HCWs. PPE's have been reported to cause adverse health and performance effects during extended usage/1/. Also it has been found that facemasks will increase to CO2 levels inside the mask up to 2000-3000 PPM/2/. HCWs are already acknowledged among

the professions with increased occupational respiratory diseases such as asthma./3/ According some studies the total inward leakage (TIL) of face masks differ remarkably from the material efficiency being in the range of 10%-25% for N95 masks and 25%-50% for surgical masks /4/.

Special ventilation arrangements (like hoods and local supply and exhausts) have been studied and proposed by research for patient wards. Yet, they are not common in hospitals as such arrangements may carry a high additional cost and /or challenge the treatment practices so that they are not considered sufficiently practical for wider use.

The reseach question behind this study is, whether it would be possible to provide better protection while maintaining comfort by means of ventilation and air diffusion with the resources and limitations of current hospitals and treatment processes.

2. Current practices in patient rooms

2.1 Patient Wards ventilation

The ventilation rates in patient wards vary quite much between countries and hospitals. Quite common range in Europe is between 2 ACH to 4 ACH, but even values up to 6 ACH /5/ are recommended. These corresponds in typical 20 m2 single patient ward to 33 l/s, 67 l/s, and 100 l/s outside airflow rate. The typical reasonings for elevated airflow rate are increased amount of odours from patients and medication provided and the treatments given in wards. It is also wort noting that even in one patient ward the occupation varies during the day due to treatments and visitors. Thus, the ideal ventilation arrangements in patient ward would enable minimum ventilation rate for sustainable operation but have flexibility for elevated air flow rate for varying situations in a ward.

Typical patient ward ventilation system is based on mixing ventilation principle without any special considerations. The maximum cooling load in a typical patient ward is about 500W, which means that an additional room cooling is often needed. This is often provided by chilled beams or radiant panels.

2.2 Isolation Room ventilation

A commonly used ventilation rate in European isolation rooms is 12 ACH. Defining the airflow rate based ACH is arbitrary, because ultimately the target of ventilation is to reduce the infection risk caused by a source, which is not depending on the room size. In infection isolation room the source is the patient. In current work within CEN TC156 WG18, Hospital Ventilation standardization workgroup the ventilation rate is defined based on the patient source. /6/ In this way it is possible to determine the targeted protection degree / dilution rate in an isolation room with a patient. With a typical breathing rate of a sedentary person, 15 l/min to reach 1:1000 dilution rate (average, based on complete mixing) a 200 l/s ventilation rate would be required. This air low rate corresponds to 12 ACH in a 60m3 room, but ACH would be different in different size rooms as the ventilation rate should be kept the same to meet the dilution criteria.

The isolation room ventilation system is typically designed to use only outside air apply mixing ventilation principle and thus assuming that the contamination is equal all over the space. In some protective isolation applications, such as burns patient wards, also protective zone ventilation principle is applied. But in such use case the ventilation rate used is much higher.

2.3 HCW work in a patient room

The primary reason for the HCW to enter the patient room is to nurse the patient. This nursing takes place in close proximity of the patient and in acute setting the patient spend most of one's time at patient bed.

As HCWs spend much time close to the patient, it is important to ensure that the exposure is minimized during HCW – patient encounters. The challenge in such situation is that HCW will be directly exposed to exhaled air from patient and vice versa. This is illustrated by a smoke visualization in a breathing mannikin study in Figure 1.

Fig. 1 – HCW exposure to patient exhalation in close proximity treatment situation./ 7/

3. Exposure risk of HCW while treating a patient

3.1 Variation of the HCW Exposure risk in isolation room

The exposure risk of a HCW, while treating patient in an isolation room has been studied in /7,8/. The study was made using breathing mannikins and

tracer gas as well as smoke visualizations.

The research focused on the HCW exposure risk in different locations of isolation room and on the influence of ventilation arrangements in the isolation room. The outdoor ventilation rate during the experiments was maintained at 170 l/s and patient breathing rate 10 L/min..

The HWC exposure risk varies largely depending on the location within the isolation room. While working close to patient the exposure risk can be up to 10 times higher than what can be expected from the exhaust concentration. The results, while using overhead mixing ventilation is presented in Figure 2./7/ Thus, instead of having 1:1000 degree protection HCW may only have compromised 1:100 protection, while working in a typical position close to patient.

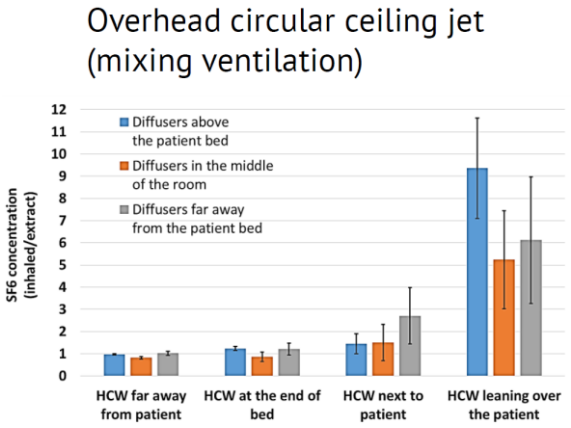

Fig. 2 – Influence of room position and ventilation outlet location on the HCW exposure in an isolation room./7/

Also, local downward flow from the ceiling was studied in the same research. When all the air was supplied on top of patient it was possible to reduce the elevated exposure, but with the consequence of high thermal discomfort, which makes this application impractical.

3.2 Influence of ACH on the HCW exposure

In fully mixed conditions it is assumed that the relative exposure is a function of the air flow rate, in other words doubling the supply airflow rate would half the concentration and thus exposure.

However, in close proximity work this may not be true as the local conditions will impact the exposure. The influence of ACH on the HCW exposure in such conditions has been studied by /8,9/, where Intake fraction, IF, has been used to illustrate relation of inhaled contaminant dose by HCW to total contaminant released to a patient room.

Figure 3 shows results from/8/, where two different air diffusion principles were measured using different air change rates. As a benchmark, in fully mixed conditions, where no direct exposure from patient to HCW occur, the IF fraction for 12ACH, 6ACH and 4 ACH would respectively be 0,1% (= 10 L/min /60s / 170 L/s), 0,2% and 0,3%. Thus, the HCW worker exposure in close proximity during those measurements have been clearly above the calculated overall room exposure. The exposure was approximately 1,5 to 1,7 times higher with the LDV and 3,2 to 5 times higher with the MV compared to calculated fully mixed condition. To put this ratio in scale it is comparable to using a surgical mask instead of N95 mask by HCW (TIL). It can also be noted that in MV situation the relative reduction in exposure, when increasing the airflow, is diminishing.

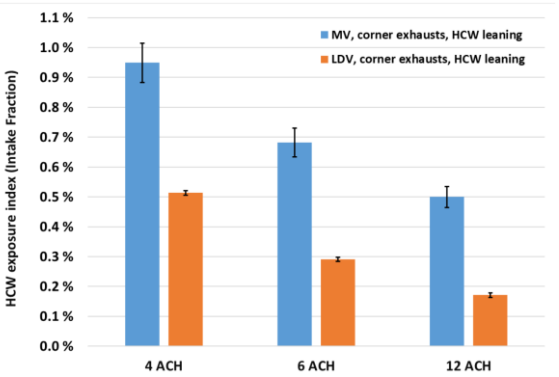

Fig. 3 – Influence of air diffusion principle and ventilation rate on the HCW exposure in an isolation room./8/

4. Development of a protective airflow system for HCW protection

Prior research clearly points out the challenge of increased exposure risk for HCWs in their daily work. Likewise, should the HCW carry an infection they also pose an increased risk to patients. And, especially from the point of ventilation profession it is important to understand that typical general ventilation is incapable to cope with close proximity work. It is not at all sufficient to compensate this gap with general ventilation efficiency indexes as the scale of risk is beyond that.

Thus, specialized ventilation and air diffusion practices should be implemented to provide enhanced protection for HCWs. However, as noted earlier it is challenging to implement any measures in practical hospital projects that would cause significant cost increase and especially would necessitate changes on the work practices of HCW.

Understanding this the targets and boundary conditions were set for the protective airflow system development including; usable airflow rate (Patient Room 30-70 l/s, Isolation room 200 l/s), cooling load requirement taking into account good

comfort air quality and acoustic conditions, and installation and operation of ventilation system in such a way that it don't limit or change HCW practices.

4.1 Protective Airflow system concept

The basic principle of the designed protective airflow system is presented in Figure 4./10/ It is based on the use of parallel air streams supplying air towards patient bed that are created by two adjustable supply air diffusers located on both sides of the patient bed.

Fig. 4 – Protective airflow system concept, patient room. /10/

During the development phase the airflow and temperature parameters have been optimized to provide both optimal protection and comfort conditions.

The same system principle has been applied for both normal ward and isolation room resulting in two variants of the system based on the different boundary conditions.

The patient ward system is based on two inward jets that are integrated with a radiant panel to provide necessary cooling and personal comfort control, like presented in Figure 4. The dynamic airflow is applied to be able to provide sustainable operation for patient only situations and protective conditions for HCW patient interactions.

The isolation room system has slightly different airflow principle; due to high airflow additional airflow patterns are directed towards sidewalls as shown in Figure 5./10/ The isolation room system has also dynamic operation principle to allow sustainable operation, when room is used for normal patients.

Fig. 5 – Protective airflow system concept, Isolation room. /10/

5. Testing of protective airflow system

5.1 Test program

The testing and development of the protective airflow system was conducted in a climate chamber of Turku University of Applied Sciences that was initially built for isolation room testing. Two breathing mannikins were used to allow controlled breathing performance of both patient and HCW as shown in Figure 6.

The research was focused on the close proximity interaction that was in earlier research found to be the most challenging as well as most common situation in patient work. The focus of the research was to measure and minimize the HCW exposure to contaminants exhaled by a patient. Diluted solution of SF6 was used as a marker for contaminant in the same manner as in previous research/7,8/ to make the results comparable. The HCW exposure and protective efficiency of the airflow system was studied with different airflow settings for both patient ward and isolation room.

Airflow pattern was visualized by smoke to illustrate system performance and measurements by omnidirectional sensors were used to ensure desired air movement over patient bed.

The indoor air quality provided by the protective airflow system was studied by means of local mean age of air. In addition to HCW exposure experiments, tracer gas experiments were carried out to measure the local mean age of air in the patient breathing zone (in the inhalation) and in the main exhaust. In the measurements, another tracer gas (N_2O) was released to the supply air duct and hence it spread to the test room with the supply air.

Thermal comfort conditions of the patient were assessed using thermal mannikin. In the experiments, the thermal manikin was lying on the bed on her back with a duvet cover on (see Figure 6). The thermal manikin is equipped with a sensor network capable of measuring thermal comfort. In the test, the manikin was dressed with a typical patient outfit consisting of underwear (underpants

and bra), socks, long pants, and a long sleeved shirt. The clo-value (clothing insulation) of the outfit was measured to be 0.5 clo (K*m2/W). The total clo-value for the manikin lying on the bed (on a mattress) with clothing and duvet cover on was measured to be 1.5 clo. For thermal comfort assessment, the metabolic rate of the manikin was set to 0.8 met, which is close to adults (female) at rest. In the experiments, the whole-body thermal comfort was measured in steady state conditions. The thermal comfort was assessed with predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) indices.

The room temperature was maintained at 24°C, which is a common value in patient room environments.

5.2 Smoke visualization of the protective airflow

Firstly, smoke visualization was used to demonstrate the protective airflow performance and to show the airflow pattern of protective flow, which is shown on Figure 6.

Secondly smoke visualization was used to demonstrate the impact of the protective airflow to the exhaled air of the patient. Figure 7 shows the outbreath of patient with protective airflow pattern with minimum 30 l/s supply air flow (Test Condition 1 in a regular patient ward situation) and Figure 8 shows the spreading of the exhaled air of the patient, when the protective flow is in use and the ventilation rate is 70 l/s. (Test Condition 2)

Figure 9 shows the exhalation flow pattern, when protective airflow is applied in isolation room conditions with total airflow rate of 200 l/s.

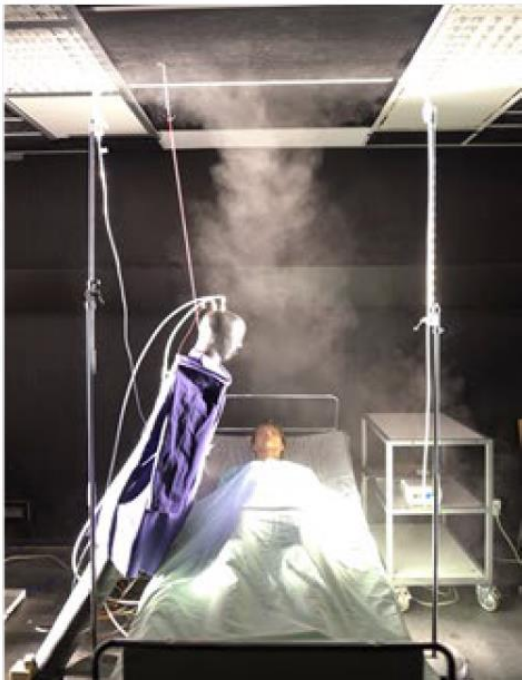

Fig. 6 – Protective airflow pattern at 70 l/s flow rate.

Fig. 7 – Patient outbreath witt protective airflow pattern in isolation room at minimum 30 l/s flow rate.

Fig. 8 – Patient outbreath with protective airflow pattern in isolation room at 70 l/s flow rate.

Fig. 9 – Patient outbreath with protective airflow pattern in isolation room at 200 l/s flow rate.

5.3 Protection efficiency performance of protective airflow system

The protection efficiency indexes for three presented test cases are shown in Table 1.

Tab. 1 – Protection efficiency index, 3 test conditions.

Test Condition	Qsupply [l/s]	ACH	HCW Exposure Ratio (Inhaled/Exhaust)	Intake Fraction IF
1 Patient Ward	30	2	1,7	0,78 %
2 Patient Ward	70	5	0,78	0,17 %
3 Isolation Room	200	14	0,83	0,07 %

The performance of protective airflow with only minimum airflow of 30 l/s is incapable to fully overcome the local exposure challenge – the full mixing indexes with 2 ACH would be for HWC Exposure Ratio 1,0 and Intake fraction, IF, 0,6%. Yet, compared to values from previous research in Figure 3 it can be noted that the Intake Fraction is clearly better than with general mixing ventilation with 4 ACH.

The actual protective airflow mode in patient ward with 70 l/s is able to provide better than fully mixed condition even in the most critical close proximity treatment situation (IF value 0,17% compared to 0,25% in fully mixed condition). Comparing earlier research, it's performance is in the magnitude of 5 times better than mixing ventilation at the same airflow rate and more than 2 times more efficient than LDV system both tested in/8/ and based on the results shown in Figure 3.

In Isolation room test the applied airflow rate was 200 l/s (Test Condition 3) following CEN TC156 WG18 work /6/ leading into 14 ACH in the test room used. Like in the patient ward case the protective airflow performance surpasses the fully mixed condition in close proximity situation. Additionally, it can be seen that, when a functioning protective airflow pattern is in place, it is possible to get full use of the increased airflow – the ratio of the IF factors 0,07%/0,017% is quite close to the ratio of airflow rate between patient ward and isolation room systems.

5.4 Indoor Air Quality performance of protective airflow system

The local mean age of air in the inhalation of the patient was found to be constantly smaller than in the exhaust. Although the differences were small occasionally, the results imply that the supply air distribution was able to provide fresher air locally to the patient bed area compared to the exhaust, even with the lowest flow rate, where no clear downward flow towards the patient was observed by smoke test.

5.5 Thermal comfort performance of protective airflow system

Thermal comfort measurement results for the whole body are shown in Table 2. Despite that all PMV values were slightly negative, generally the measured thermal comfort was on a good level. Such a minor difference is easily adjustable by radiant panel or room temperature adjustment.

Tab. 2 – Thermal comfort indexes, 3 test conditions.

Test Condition	Qsupply [l/s]	Tsup-Trm [°C]	PMV	PPD%
1 Patient Ward	30	-4	-0,4	8 %
2 Patient Ward	70	-4	-0,5	11 %
3 Isolation Room	200	-4	-0,6	13 %

However, before implementing such a special airflow system in real life conditions, it was decided to confirm the thermal comfort evaluation by using human subjects

6. Perception of air movement and thermal comfort in patient room

The purpose of the study was to conduct human subject experiment about perception of air movement and thermal comfort of participants laying in a hospital bed in patient ward with the protective airflow system.

The room conditions during the test were kept the same as in previous test with protective airflow system as the purpose was to validate the acceptability of thermal comfort conditions assessed earlier using thermal mannikin.

6.1 Description of test method

The experiment was done in N Universitys' HVAC laboratory in N, N. A full-scale mock-up simulating a simplified hospital patient room was built into the laboratory. A similar procedure had been developed in earlier patient room testing /11/

Two conditions 1 and 2 were used by varying airflow rate between minimum airflow mode and protective mode. The details of the test procedure is shown on Figure 10 and explained below.

A repeated measures design was used, meaning that each participant went to both test conditions and served as their own control minimizing the effect of participants' individual differences on results.

15 test participants (8 females, 7 males) were used

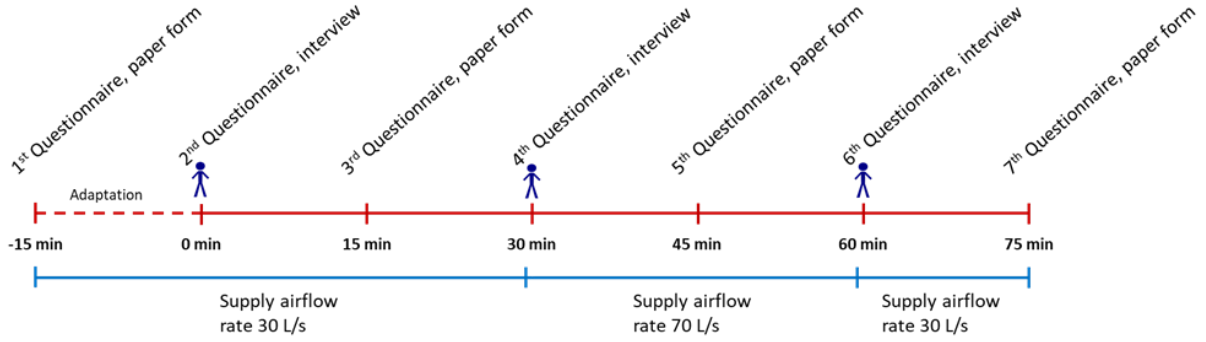

Fig. 10 – Test procedure for air movement and thermal comfort evaluation in patient room.

with mean age 28 years. The subjects used similar standard hospital clothing as was used with thermal mannikin. The thermal isolation of clothing, blanket, pillow and mattress was 1.5 clo, measured with thermal manikin.

The participants were reclining in a hospital bed and listened an audio podcast.

Fig. 11 – Participants' position, clothing and the adjustment of the blanket during the experiment

Overall thermal sensation was asked using seven-point response scale from ISO standard 7730 (2005): Hot (3), Warm (2), Slightly warm (1), Neutral (0), Slightly cool (-1), Cool (-2), and Cold (-3).

Besides overall thermal sensation and comfort, local thermal comfort, thermal satisfaction and pleasantness of the air movement, and perception of airquality was asked.

Symptoms, such as headache, feeling unwell, and nose, throat and eye symptoms were assessed with five-point response scale (1 = Not at all, 2 = Slightly, 3 = To some extent, 4 = Quite a lot 5 = Very much).

In addition, questionnaires included so called "dummy questions" that were used to distract participants focus only on thermal environment. Dummy questions were related to interior design and ergonomics.

6.2 Results - thermal comfort

Thermal comfort results are presented in figure 11 and in tables 3, 4, 5. In figure 12, the box contains the middle 50 % of the votes, the central bold line is the median of the distribution and stars represents outliers. The overall thermal perception by participants was very good for both test cases.

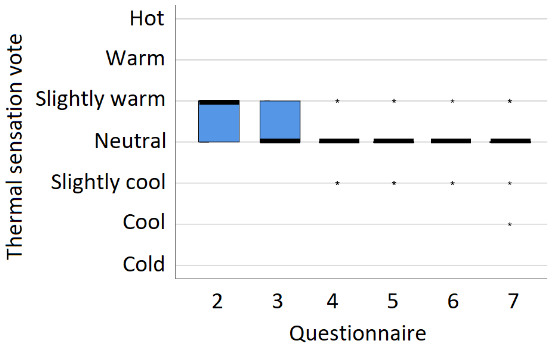

Fig. 13 - The distributions of thermal sensation votes by questionnaires. The distribution is lacking the box if the middle 50 % of the votes are placed on together with the median.

Tab 3. Average thermal comfort results by questionnaire. (TSV = thermal sensation vote, and PD = percentage dissatisfied with the thermal environment).

Questionnaire	2	3	4	5	6	7
TSV	0.5	0.3	-0.1	-0.1	0.1	0.1
PD [%]	0	0	7	20	13	7

Tab 4. Average thermal comfort results by test condition. (TSV = thermal sensation vote, and PD = percentage dissatisfied with the thermal environment).

Test condition	1	2
TSV	0.2	-0.1
PD [%]	5	13

Local thermal sensation was asked using open questions, where face, hands, feet and middle body were mentioned. Both warm and cold sensation was mentioned as well as neutral.

6.3 Results – Perception of air movement and quality

Perception of air movement results are presented on tables 5 and 6. The overall perception by participants was very good for both test cases and felt even more pleasant during test condition 2, which was protective mode.

Table 5. Average perception of air movement by questionnaire. The scale for perception is Very unpleasant (-2), Slightly unpleasant (-1), Not pleasant or unpleasant (0), slightly pleasant (1), Very pleasant (2)

Questionnaire	2	3	4	5	6	7
Participants	7	13	73	87	53	40
Perception	0.0	-0.5	0.1	0.2	0.0	0.3

Table 6. Average perception of air movement by test condition. The scale for perception is Very unpleasant (-2), Slightly unpleasant (-1), Not pleasant or unpleasant (0), slightly pleasant (1), Very pleasant (2)

Test condition	1	2
Participants perceiving air movement [%]	28	80
Perception	0.0	0.2

Local perception of air movement was asked using open questions. Sensation on face and hands were mostly mentioned. Also, sensation on middle body was mentioned by some.

The air quality was perceived rather good in both test conditions (4.4 in test condition 1 and 4.5 in test condition 2, scale: 1= stuffy, 6=fresh).

6.4 Results – Symptoms

The mean values of perceived symptoms in both test conditions are presented in table 7. All mean values are below 2 (slightly) with no difference between test conditions. Minor difference was seen in perception of eye symptoms. However, the practical meaning of this difference is negligible.

Table 7. Perception of symptoms by test condition.

Test condition	1	2
Sweating	1.3	1.3
Nose symptoms	1.1	1.0
Throat symptoms	1.3	1.3
Eye symptoms	1.6	1.7
Feeling unwell	1.0	1.0

7. Conclusions

HCW are exposed to elevated infection risk in their daily work and act as an agent spreading infection within hospitals. The especial concern is work in proximity of patient, where the exposure risk is elevated up to 5-10 times and cannot be eliminated by means of general ventilation. Using constantly personal respiratory protection is not a sustainable solution due to adverse health effects.

A dynamic protective airflow system has been developed to eliminate/reduce exposure even in proximity work and its performance has been studied throughout from HCW protection and patient comfort point of views.

The tested system can provide a cost-efficient and sustainable solution for HCW protection without causing disturbance to daily work of HCWs. The most importantly HCW exposure can be remarkably, even down to 1:5-8, reduced in proximity work. Results also show that this can be made without causing thermal discomfort for a patient, which is a typical challenge for many local ventilation arrangements, such as LDV presented in earlier research.

8. Acknowledgement

The research has been partly funded by Business Finland.

9. References

[1] Ippolito M. et al. Medical masks and Respirators for the Protection of Healthcare Workers from SARS-CoV-2 and other viruses, Review. Pulmonology, Vol. 26, Issue 4, July–August 2020, Pages 204-212.

[2] Geiss O. Effect of Wearing Face Masks on the Carbon Dioxide Concentration in the Breathing Zone. Aerosol and Air Quality Research, Vol 21, Issue 2, 2020.

[3] McDonald J C, Chen Y, et al. Incidence by occupation and industry of acute work related respiratory diseases in the UK, 1992–2001. Occup Environ Med;62:836–842.

[4] Bagheria G, Thiedea B, et al. An upper bound on one-to-one exposure to infectious human respiratory particles, Dec 2021 ,PNAS 2021 Vol. 118 No. 49.

[5] HTM 03-01, Specialised ventilation for healthcare buildings June 2021, NHS, UK.

[6] CEN TC156 WG18, Hospital Ventilation, Working draft document, 2022.

[7] Kalliomäki P., Koskela H, Suojaava ilmanjako sairaaloiden erityistiloissa, Protective Airflow in Hospital isolation rooms (In Finnish), TuAMK Report 244, 66p. 2018.

[8] Kalliomäki P., Koskela H, et al, Assessing the risk to healthcare workers of hospital-acquired infection from patients infected with aerosol-transmissible pathogens, IOSH Research Report, 79p. 2020. https://iosh.com/reducing-hospital-infections

[9] Berlanga F, Olmedo I, Experimental assessment of different mixing air ventilation systems on ventilation performance and exposure to exhaled contaminants in hospital rooms. Energy & Buildings 177 (2018) 207–219.

[10] https://www.halton.com/technology/protective-airflow/

[11] Maula, H., Kalliomäki, P. and Koskela, H. (2021). Thermal comfort in a hospital isolation room – A laboratory study. Proceedings of Healthy Buildings 2021 Europe conference, 21-23 June 2021. Virtual conference.

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.