Experimental and numerical evaluation of a new visor concept with aerodynamic sealing to protect medical professionals from contaminated droplets and aerosols

Nuno Rosa1 | Mário Jordão1 | José Costa1 | Adélio Gaspar1 | Nuno Martinho1,2 | António Gameiro Lopes1 | Miguel Panão1 | Manuel Gameiro da Silva1

1Univ Coimbra, ADAI, Department of Mechanical Engineering, Coimbra, Portugal
2Polytechnic Institute of Leiria, Department of Mechanical Engineering, Leiria, Portugal

Correspondence
Nuno Rosa, Univ Coimbra, ADAI, LAETA, Department of Mechanical Engineering, Rua Luís Reis Santos, Pólo II, 3030-788 Coimbra, Portugal. Email: nuno.rosa@uc.pt

Abstract
The fast spreading of the SARS-CoV-2 virus led to a significant increase in the demand for personal protective equipment (PPE). Healthcare professionals, mainly dentists, work near the patients, increasing their risk of infection. This paper investigates the effectiveness of an air-curtain sealing effect in a newly designed visor developed to reduce the risk of contracting a respiratory infection. This PPE was developed by computational fluid dynamics (CFD) modeling. CFD results show that the aerodynamic sealing in this PPE device effectively protects the user's face by 43% from a contaminated environment. The experiments considered two different tests: one using a tracer gas (CO2) to simulate a gaseous contaminant inside and outside the PPE face shield and a second test using smoke to simulate aerosol transport and evaluate the PPE efficiency. The particle concentration within the aerodynamically sealed PPE was evaluated and compared with the protection efficiency of other PPE. Results show similar protection levels for particles in the 1–5 μm range between the prototype and a KN95 respirator. The combined use of this novel PPE with aerodynamic sealing and a physical mask (KN95 or surgical) produced protection efficiency values within the range of 57%–70% for particles greater than 0.5 μm. This study reveals the potential of using an air curtain combined with a face shield to reduce the risks from contaminated environments.

KEYWORDS
aerodynamic sealing, air curtain, healthcare professionals, personal protective equipment, SARS-CoV-2

1 INTRODUCTION

Since the early XXI century, the world has faced five major pandemics. The first one with the SARS virus in the early 2000s, MERS and the swine flu around 2010, Ebola and Zika in the mid-2010s, and recently the COVID-19 disease with the new virus SARS-CoV-2. And yet, Jones et al. argue that pandemics are likely to increase in this century. Therefore, each pandemic demands new technological innovations to improve the response time and mitigate the spreading of new viruses. The transmission of the SARS-CoV-2...
virus occurs through aqueous aerosols suspended in the air (size <5 μm) and larger droplets (size >5 μm). An infected person emits contaminated particles through coughing, sneezing, talking, and even breathing.

It is known that transmission via aerosols can occur over long distances, especially within enclosed spaces. Factors such as physical distance, the emitted number of infectious virus particles and the exposure time contribute to the transmission risk of airborne diseases. Additionally, ventilation, airflow, CO2 level, temperature, and humidity should be considered. This puts in particular risk people with long stay periods in enclosed spaces, such as medical offices.

Several health organizations suggested the control of the viral load present in these liquid particles through face masks and social distancing as the two main strategies to avoid getting infected and most outdoor situations.

11 Even when the spray significantly dilutes the virus, the research reported that this type of contamination is not the most common. The larger droplets’ impact on nearby surfaces constitutes an additional risk of infection if hand hygiene is inadequate, although research reported that this type of contamination is not the most common. Even when the spray significantly dilutes the virus, the continuous production of droplets for long periods still presents a non-negligible health risk. Also, if the patient is asymptomatic, the risk of infecting another person is still present. Therefore, it is essential to develop protection systems for dentists and their staff, which require adequate knowledge of the drop size distribution in dental sprays and their relation with the viral load.

The aqueous sprays of dental rotary equipment contain a multitude of droplets, the majority of which are in sizes ranging from 0.9 to 5 μm. Moreover, the magnitude of virus sizes is around 0.1 μm. Thus, the virus can attach to the larger liquid particles (>1.0 μm) produced, for example, by the human respiratory system. The several strategies implemented to protect healthcare workers from droplets emitted by infected patients include pharmaceutical, and non-pharmaceutical methods such as personal protective equipment (PPE). These are crucial protection elements in medical setups and most outdoor situations. Currently, safety recommendations for dentists include wearing gloves, gowns, eye protection devices (such as a face shield), a surgical mask, and a NIOSH-certified N95 respirator when conducting procedures known to generate aerosols, according to OSHA PPE standards.

Several studies compared different mask solutions and entire PPE systems, concluding that full mask respiratory devices with air circulation mitigate CO2 rebreathing, and air-shade systems provide greater comfort in prolonged usage while giving medical staff the freedom to perform their tasks. In particular, face shields showed a substantial aerosol reduction, around 55%, in short-term exposure of healthcare workers to large infectious aerosol particles. However, smaller particles remain airborne for more extended periods, potentially flowing around the face shield and being inhaled by the user. Ronen et al. also found that the shield geometry significantly impacts performance. Namely, they found that a shield blocks ten times more particles than a surgical mask for sizes <0.3 μm, although finding no noticeable difference for bigger particles. N95 respirators offered better protection to the user than surgical and cotton masks for 5 μm particles, even when not adequately fitted. Some authors tried to develop novel PPE systems capable of protecting healthcare workers, using unconfined air curtains as face shields block the entry of particles. However, the interaction with air-circulating flows inside the room or even the person’s motion can disrupt the desired protective effect.

The present work explores the aforementioned aerodynamic strategy of an air curtain to control the aerosol concentration close to a person’s face but considers a face shield to improve the protective efficiency of the PPE. The novelty of the work is the development of a new PPE which can block droplets with the face shield and is provided with an air curtain that protects the user against dispersed aerosols. The newly designed PPE prototype used in the experiments reported here resulted from a numerical study of several approaches. These numerical approaches will be discussed in detail in another scientific paper. The final prototype consists of a face shield with an air curtain that blocks suspended particles. The PPE prototype was subjected to two ensembles of preliminary experiments to study its effectiveness. The first ensemble of experiments used a tracer gas (CO2) to check the prototype’s efficiency in blocking gaseous contaminants from entering the user’s breathing zone. The second set of experiments used smoke particles to simulate aerosols and evaluated their concentration within the user’s breathing zone while “wearing” different PPEs, as a means of comparing the proposed solution with other designs. The following section details

Practical Implication:

- The air-curtain aerodynamic sealing effect in a newly developed visor (MASK4MC, *mask for medical care*) significantly reduces the risk of inhaling droplets and aerosols with potential viral load.
- Experimental and numerical results indicate that the protection efficiency of MASK4MC is 40%–50% when exposed to a tracer gas.
- The combined use of MASK4MC and a face mask (surgical and KN95) leads to protection efficiency values within the range of 57%–70% for particles greater than 0.5 μm.
the prototype design, the experimental setup devised to evaluate its performance, and, finally, the experimental procedures.

2 | MATERIALS AND METHODS

2.1 | Description of the air curtain sealed prototype visor

The PPE under research, henceforth designated as MASK4MC, was designed to be a comfortable fit for any person and still allow the healthcare worker to use a surgical mask or a KN95 respirator and specialized dentist loupes. Figure 1 shows in detail the MASK4MC prototype. The inner surface of the front face shield (A) of the MASK4MC bounds the air curtain supplied by a plenum (B), and a complex support system (D and E) joins both components. The front face shield also serves as a physical barrier, protecting the user from particles emitted by the rotary equipment by preventing their impact on his face. The air supplied by an air compressor system enters the MASK4MC from a tube with 8 mm in diameter on its upper part (C in Figure 1A) and splits into two inlets before the plenum (F in Figure 1B). The flow configuration for the air ejected from the plenum to the inside part of the MASK4MC through eight different outlets (G in Figure 1B) was the most challenging part of the MASK4MC to design in order to ensure a uniform air velocity across the jet-outlet slots 1, 2, and 3 while ensuring higher velocity in outlets 4 (see Figure 1B).

To generate a uniform and stable air curtain from the airflow issued by distinct wall jets, the plenum should ensure a uniform pressure drop at all outlets. Furthermore, the small plenum volume (0.075 L) increases the difficulty of controlling the airflow (K in Figure 1C) and pressure drop at outlets. The uniform pressure drop is achieved in all plenum outlets by using: (1) four polymeric perforated filters (I in Figure 1C), drilled with holes 1 mm in diameter and spaced 2 mm apart; (2) a wall upstream of the jet slots to increase the uniformity of flow near the air vents (M in Figure 1C). The plenum is composed of two polymeric coviers, and they are assembled to each other using four screws (J in Figure 1C). Lastly, the support system has a cog wheel-buckle system in the back made of polymeric material. This system enables the adjustment of the MASK4MC prototype to the user’s head, regardless of its size. In the final version of this PPE, there is also a foam pad in the plenum inner side, providing greater comfort for the user. This foam pad also works as a sealant to avoid dragging potentially contaminated air inside the MASK4MC from the top part. This novel PPE concept was registered in Portugal in the form of “utility model,” and one final version of this prototype was already manufactured (Figure 2).

2.2 | CFD model and PPE design

The CFD 3D models were developed and solved using commercial software ANSYS CFX® to simulate the airflow within the supply-air plenum and in the inner air-curtain domain. The human CAD model was generated via a 3D-laser surface previously scanned by Martinho, N. The real model consists of a female thermal-breathing manikin, which was further used for experimental tests. The MASK4MC design did not consider the effect of human breathing on the air curtain in this initial design stage, since the dentists should wear a face mask. Therefore, the present results are reliable for the performance characterization of the developed visor. Simulations of the plenum and the air curtain were conducted using distinct CFD models to reduce computation time and effort. Results of the air velocity profiles at the jets slots from the plenum were imported and used as boundary conditions in the visor and air-curtain model. Unstructured tetrahedral grids were used for the spatial domains’ discretization. The grid was refined near solid boundaries (manikin head and visor), to reach a non-dimensional near-wall distance y+ < 1 in the airflow domain. To improve the spatial discretization, a 10-layer grid with nearly constant spacing was set near the visor’s inner surface considering the first cell height as 10-4 mm. This refined layer grid size was then smoothly increased for a gradual transition into the inner calculation domain. At solid boundaries, the no-slip condition is specified for the momentum conservation equations. Grid dependence tests were carried out to ensure that the numerical results were grid-independent leading to a total of 1.7 million nodes and ~6.3 million cells. The mesh quality is automatically checked by ANSYS CFX meshing in terms of orthogonality, aspect ratio, and expansion factor.

A multicomponent flow model was adopted, by using two distinct fluids with identical physical properties. The first fluid corresponds to a “clean air – Air at 25°C” that will be blown through the plenum slots, forming wall jets inside the visor, and will be responsible for sealing and preserving safety in the inhalation domain. The second fluid represents “contaminated air” that occupies the surrounding environment. The model simulates the flow and mixing between the two fluids, allowing verification of the PPE protection in an extreme case scenario, where the environment around the user is fully contaminated. The volume fraction of contaminated air (VFC) within the breathing zone is then numerically predicted.

To account for the effects of turbulence, the RNG- k-ε and Shear Stress Transport (low-Re turbulence) models are used to compare differences between CFD predictions of the airflow field and fluids’ mixing. The RNG- k-ε turbulence model is the most commonly used to simulate turbulent flows for CFD design. However, this model does not accurately predict the flow with boundary layer separation and has difficulty in solving the near-wall region and vortex flows. The SST model uses the standard k-ε model in the fully turbulent region of the flow and the k-ω model in the near-wall region. This model is suitable for representing the boundary layer and allows a more refined wall treatment. In these steady-state simulations, advection terms were discretized with a second-order scheme for momentum and with a first-order scheme for turbulence equations. The convergence criteria for all variables (momentum, mass, turbulence, and volume fractions) were set to 10^-6, and domain imbalance was set to be lower than 1%. The simulations were performed using an
Intel Core i9-7900x CPU@3.30GHz with 32GB RAM – 20 logical processors were used during calculation.

Figure 3 presents a schematic representation of the calculation domain, including the identification of the points for monitoring the numerical results. The initially assumed conditions for every steady-state simulation are (1) clean air within the visor safety domain (VFC = 0); and (2) contaminated air around the user (VFC = 1.0). The boundary conditions for the simulations are (v. Figure 3) A—contaminated air opening-type boundary with 0 Pa pressure, and turbulence intensity of 5%; B—clean air inlet, jets with air velocity profiles obtained from the first model (plenum). In the plenum model, the boundary conditions are C—Inlet mass flow rate of 24.5 L/min; and 0 Pa in the outlets. A matrix of 12 points at the nose level and 26 points at the mouth level (Figure 3) were used to calculate the average VFC.

In the early stages of the geometry development, the jet velocities were considered normal to the outlet sections (Figure 4). A tilt angle in the lateral jet allowed a better airtightness of the face shield.

FIGURE 1  Air-curtain sealed visor prototype geometry. (A) Face shield components; (B) plenum geometry; (C) inner plenum components and geometry
A tilt angle of 26.57° plus an increased velocity of the lateral jet were considered to neutralize the entrainment of contaminated air through the lateral border of the face shield. Furthermore, the air velocity of the front jets was limited to not exceeding 0.25 m/s near the breathing zone for better comfort. Figure 5 shows the preliminary results for the VFC in the earlier stages models, with no lateral jet tilt (Figure 5A) and a widthwise tilt angle of 26.57° (Figure 5B). As may be observed, the lateral jet air velocity and tilt angle significantly influence the PPE performance. These models consider a jet-slots width of 4 mm, and the lateral jet flow is near the face. However, in the final version of the plenum, the jet-slots width was decreased to 2 mm, to reduce the total airflow rate. This allows better control of airflow inside the plenum. Moreover, decreasing the airflow rate results in lower noise inside the plenum and discomfort. After this first model, several approaches were studied until the final conceptual version of the PPE (Figure 1).

2.3 | Experimental setup and protocol

The experiments were carried out in a wood-framed chamber of dimensions 1×1×2 m, with the walls made of transparent rigid plastic sheets (Figure 6). Preliminary tests demonstrated a good sealing of the chamber: a residual air infiltration rate of only 0.047 h\(^{-1}\) as obtained by the tracer-gas decay method. The temperature and relative humidity inside the chamber were kept constant with values of 21 ± 0.5 °C and 58 ± 2.0%, respectively. A fan (Figure 6B) inside the chamber homogenizes mixing during the initial insemination of the indoor air with a contaminant. The manikin used in CFD simulations was seated inside the chamber (Figure 6A) to simulate a user of the PPE.

To study the protective effect of the newly developed PPE against contaminated air, the first ensemble of experiments used a fire extinguisher (Figure 6C) to inflate CO\(_2\) (contaminant) into the chamber via an inlet port (Figure 6D). Three CO\(_2\) sensors (Colswc VOC logger) measured the CO\(_2\) contaminant concentration (Figure 6E). The first sensor was placed close to a wall of the chamber, the second sensor was fixed on the outer surface of the MASK4MC prototype’s face shield and the third sensor was located inside the MASK4MC prototype visor, close to the mannequin’s face. An in-house LabVIEW™ program was used to register all sensors’ data (CO\(_2\) concentration, air temperature, and relative humidity). Additionally, a fourth CO\(_2\) sensor (Omega AQM-102) located inside the chamber (Figure 6F) allowed the real-time checking of the indoor CO\(_2\) concentration, air temperature, and relative humidity. An air compressor, placed outside the chamber (Figure 5H), supplied the MASK4MC prototype (Figure 6G) with the required ventilation airflow rate for studying the air curtain. The compressed air system is composed of a compressor tank, a pressure converter (DISA Type 55 D46), a pressure control unit (DISA Type 55 D 44), and a compressed air piping (≈6 bar).
For the second set of experiments, a smoke generator AEROTECH (Figure 5I) producing smoke particles from a refined Shell® Ondina oil was used to simulate the presence and dispersion of aerosol particles. This set of experiments included several types of protective equipment with different configurations, implying the use of two optical particle counters (Lighthouse HH 3016 IAQ™) assembled inside the chamber (Figure 6J). The first optical counter measured the number of particles outside the face shield. The second optical counter, connected to a tube coming from the mannequin’s mouth and issuing at its neck’s back, was used to count particles and measure the concentration in the air samples collected from the breathing zone. The list of equipment and the detailed technical characteristics are presented in Table 1.

2.4 | Experimental procedure

The first set of experiments addressed the protective ability of the developed PPE (MASK4MC) to clean the breathing zone and keep the simulated contaminant (CO₂) concentration as low as possible. After checking the proper functioning of the prototype by measuring the air velocity near the plenum outlets (jet slots) with an air meter (Fluke 975 AirMeter™), the chamber was closed, CO₂ was injected inside the chamber until its concentration exceeded 8000 ppm in the chamber sensor (Figure 6F). A small fan ensures a homogenous air-CO₂ mixture inside the chamber, that was confirmed when all CO₂ sensors (Figure 6E) measured similar values of contaminant concentration. After the homogeneous concentration stage was reached, the air valve of the MASK4MC prototype was opened. Experiments considered two runs for each airflow rate (henceforth lowest and highest) to ensure reproducibility of the results.

A similar procedure was adopted for the second set of experiments with smoke particles, where the objective was to simulate contaminated aerosol particles to evaluate the prototype’s ability to avoid the dragging of aerosol into the breathing zone. For every sampling, the particle counters suck the air during 60 s at a rate of 2.83 L/min and made a 60 s-pause after the last reading. The smoke was introduced inside the chamber for about 7 min until a reading resulted in 2400 μm/m³ on the outside particle counter. The generated particles had sizes ranging from 0.5 to 5 μm analyzed before experiments started. After reaching a homogeneous concentration of particles (approximately 5 min), the air-curtain valve was opened for 10 min to perform five sampling measurements with a time step of 1 min. To compare different PPEs and strategies, the procedure was repeated for the two airflow rates considered. The PPEs configurations considered in this work were:

1. MASK4MC with the design airflow rate of the curtain (1X);
2. MASK4MC doubling with the design airflow rate of the curtain (2X);
3. KN95 respirator (taped around the borders);
4. Surgical mask (taped);
5. MASK4MC with design airflow rate and KN95 respirator (borders not sealed with tape);
6. MASK4MC with design airflow rate and KN95 respirator (taped borders);
7. MASK4MC with design airflow rate and surgical mask;

Following the approach presented in Pan et al., the PPE efficiency can be defined as

\[
PPE \text{ efficiency } (\%) = \left(1 - \frac{N_i}{N_o}\right) \times 100, \quad (1)
\]

where \(N_i\) is the number of particles in the breathing zone, inside the PPE, and \(N_o\) as the particle count in front and outside the PPE. All tests performed with different PPE strategies focused on the potential receptor of contaminated aerosols, not the infected emitter.
Therefore, the PPE efficiency is expected to differ from other published works and standards, namely medical face masks norms, such as EN14683:2019. Forouzandeh et al. present more details on standards and test methods. Another factor contributing to differences in results is the use of smoke as an aerosol due to its different inherent nature compared with dentist procedures’ sprays, which may contain a mixture of water and saliva. However, contamination occurs through particles’ transport where the size is the main parameter, not its composition, validating the approach followed in this work.

3 | RESULTS AND DISCUSSION

3.1 | Experiment with CO₂ and validation of CFD simulations

The reference airflow rate estimated in the design phase inside the plenum was 24.5 L/min, necessary to achieve uniform jet outlet velocities of about 0.5 m/s on the forefront and 1 m/s in the plenum’s lateral outlets, respectively. Figure 7A, B show, respectively, the velocity contours in the plenum outlets and the respective average air velocity and the flow streamlines. The air velocity profile is relatively homogenous. However, the third and second air jets still have higher velocity than the one predicted during the design stage. Using a hot-wire anemometer, the measured average velocity in each exit allowed estimating an airflow rate of $26.5 \pm 3.6$ L/min. Also, possible imperfections in the PPE manufacturing could lead to a detachment of the air curtain flow from the inner surface of the MASK4MC face shield. The experiments considered an operating condition with double the mean air velocity in each exit to assess the relevancy of this detachment in the protective efficiency of the prototype. According to the measured mean velocity values, the airflow rate in this second case implied, instead, 2.3 times increase to $60.4 \pm 4$ L/min.

A CFD approach using the shear stress transport (SST) and RNG $k$-$\varepsilon$ turbulence models was used to evaluate the airflow pattern in
the region between the visor’s inner surface and the user’s face and establish its protective effect by analyzing the concentration levels of contaminated air outside the visor. The detailed analysis of the effect of turbulence models in the predicted PPE air-curtain flow field are beyond the scope of the present work; it will be the subject of another publication under development.

For the lowest flow rate, Figure 8A, B depict the volume fraction of contaminant inside and around the PPE, and the air-curtain

### Table 1: Equipment’s specifications

| Equipment                | Purpose                                                                 | Accuracy                                                                                           |
|--------------------------|-------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------|
| Fluke 975 AirMeter™      | Verify locally the operation of the PPE (Temperature, velocity, humidity, CO₂) | ±0.5°C, ±2% RH, 0.02 m.s⁻¹, 2.75% + 75 ppm                                                        |
| Omega AQM-102            | Measure chamber temperature, CO₂, humidity                              | ±0.1°C, ±3% RH, 3.0% + 33 ppm                                                                     |
| Colsw VOC logger         | Measure chamber and inside PPE conditions, CO₂, humidity, pressure, temperature | 1.0% + 20 ppm                                                                                     |
| Lighthouse HH 3016 IAQ™  | Airborne particle counters (0.3–10 μm size range)                       | 50% 0.3 μm; 100% > 0.45 μm (per ISO 21501-4)                                                       |
| Ate Aerotech smoke generator | Emission of the smoke into the air smooth and steady            | Vaporiser power: 90W max (30V; 3 A ac); 60 ml/h; shell AOnida EL                                   |
protective effect at several points around the mouth and nose. The average simulated values of contaminated air in steady-state conditions close to the mouth and nose led to protective efficiency predicted values around 43% and 50% with the SST and RNG $k$-$\varepsilon$ turbulence models, respectively. The air-curtain flow streamlines obtained with the SST and the RNG $k$-$\varepsilon$ turbulence models are shown in Figure 8C. The results show that the turbulence model has some influence, mainly due to the vorticity nature of the air curtain (Figure 8C), in which case the SST model is more robust and reliable. Furthermore, in the final version of the PPE plenum, the fourth jet could not completely seal the lateral border of the shield, causing some vortex movement inside the breathing zone. CO$_2$ tests allow understanding which turbulence model shows a better fit.

The CO$_2$ concentration recorded during a control experiment, depicted in Figure 9, shows the relative uniformity of values in the chamber, outside and inside the mask. After injecting CO$_2$ into the chamber, the sensor measuring the concentration inside the MASK4MC (Figure 9) had a slightly slower time response than the other two sensors. The delay occurred due to the constraint of the visor on the air-CO$_2$ mixture. The overshoot in CO$_2$ concentration observed in the first minutes corresponds to the fan blowing toward the sensor. Nonetheless, both the chamber and outside sensors have similar results throughout the rest of the experiment (Figure 9). Figure 9 also confirms the sudden decrease in CO$_2$ concentration when turning on the air curtain of the MASK4MC. This change was particularly significant for the reference airflow rate of 26.5 L/min and highlighted that a higher airflow rate might not be necessary to obtain the protection needed for the design developed.

Figure 10 shows the results for the protective effect of the prototype mask considering the CO$_2$ concentration normalized by the value of the sensor inside the chamber. The initial decay in CO$_2$ concentration is almost 40% between the inside and outside the MASK4MC. The two experiments depicted in Figure 10A show similar airflow behavior regardless of the switch-on instant and confirm the result’s reproducibility. The slight increase in the relative CO$_2$ concentration inside the face shield after the initial decay when the airflow is turned on indicates that the sealing is not perfect. However, the difference represents only 10% after 90 min, which is reasonably safe considering the average time of medical procedures performed by dentists. A reasonably good agreement was observed between the experimental and the CFD results, with a 3% difference using the SST turbulence model. When the airflow is doubled and synchronizing the switch-on instants in the two experiments, the results depicted in Figure 10B are reproducible and similar to the first experiments, although the decrease in the CO$_2$ concentration measured inside the prototype mask improves only 10%.

Figure 10C compares the CO$_2$ concentration of the sensor outside the prototype mask for both airflow rates considered, indicating a slight effect of increasing the airflow rate on the outside. The higher dragging affects the airflow exiting at the bottom of the PPE visor, inducing mild but additional protection. Finally, Figure 10D compares the protective effect of the airflow for the cases with close instants of airflow switch-on. The results show that gains are not substantial, and the limitations in the PPE sealing are independent of the airflow rate. The following section considers smoke to simulate contaminated aerosol particles and assess the PPE protection efficiency.
3.2 | Experiments with simulated aerosol particles

Liu et al.\textsuperscript{36} in the early studies on the aerodynamic spreading of contaminated aerosol particles in Wuhan hospitals, showed that particles with sizes above 1 μm have higher viral loads than smaller particles. Pan et al.\textsuperscript{24} stated that the aerosols produced during breathing and speaking center around 1 μm. Therefore, these authors conclude that mask performance should focus on particles larger than 0.3 μm. Furthermore, the characterization reported by Sergis et al.\textsuperscript{13} for rotary dental instruments shows that the size of droplets that can interact with contaminated saliva from a patient and eventually infect medical staff is in the range of 1 to 5 μm. Therefore, to assess the protective effect of personal protective equipment, the experiments with smoke focused on the concentration of three aerosol size classes (1, 2.5, and 5 μm). The PPE configurations under research included conventional PPE systems (KN95 and surgical masks), the MASK4MC prototype, and hybrid configurations. All conventional masks used a sealing tape to ensure no additional particle entry.
regions in the PPEs, except for the hybrid configuration joining the MASK4MC prototype with the KN95 that also considered the case without the sealing tape. Figure 11 shows the PPE efficiency obtained from Equation (1) for all configurations tested.

Amongst the several tested PPEs configurations, the lowest efficiency value is 10% for 1 μm particles when using only a surgical mask. However, the MASK4MC prototype with the design airflow rate of 26.5 L/min showed 29%–35% protection efficiency for the particles size range considered, 5% and 12 lower than the average values predicted for nose and mouth, respectively, using the SST turbulence model (Figure 8). The increase in the airflow rate to 60.4 L/min produces a marginal increase (4%–22%) in the MASK4MC efficiency compared with the designed flow rate. The increased noise inside the MASK4MC for a higher airflow rate configuration does not justify this improvement in its efficiency.

The KN95 respirator performed slightly better for particles equal to or larger than 2.5 μm but much worst for smaller particles. The outcome for particles of 1 μm with surgical masks is even lower. When adding the MASK4MC, the air curtain drags these smaller particles outside the mask, increasing its protective effect. Together with the face masks, a hybrid approach provides a second protective level increasing the minimum PPE efficiency from 29% to 33%, corresponding to the unsealed face mask. However, when sealed with tape, the PPE efficiency boosts to 57%, which is significant and evidences a limitation of conventional PPEs. The test results allow concluding that wearing two PPE provides the best protection for the user, but sealing the conventional PPE device is very effective. Arellano-Cotrina et al. reviewed the masks that dentists should use and recommended the KN95. However, within the respirator mask category, where

---

FIGURE 10 Normalized CO₂ concentration shows the protective effect of the air curtain inside the mask for two airflow rates. (A) 26.5 ± 3.6 L/min; (B) 60.4 ± 4 L/min; (C) outside the shield; (D) inside the shield.
the one developed in this work fits better, they advise its combination with a disposable surgical mask. Our results support this recommendation but add the need to develop appropriate sealing systems to avoid any bruises from prolonged use of tight masks, as noted by Darwish et al.\cite{Darwish2020}.

**CONCLUSIONS**

The development of personal protection equipment (PPE) for healthcare workers is crucial due to the critical importance of their function beyond the pandemic crisis. This paper presents the development of a novel PPE (MASK4MC) using an air curtain attached by design to the curvature of a specific visor, which provides additional protection from potentially contaminated aerosols. The results from this new PPE compared to other conventional ones show a reduction of 40%-50% in CO₂ concentration with the design airflow rate of the air curtain. This reduction was minor when doubling the airflow rate.

An experimental setup using smoke particles from 1 to 5 μm to simulate the aerosol size range allowed evaluation the PPE efficiency. The experiments showed that the MASK4MC prototype operating solo provides a minimum protection level of 29%. In a hybrid configuration joining the prototype and a KN95 face mask, this value increased 5%, but a whopping increase of 31.5% when using a disposable surgical mask. Also, these protection efficiency values implied the sealing of the face masks considered in the experiments, providing an essential guideline for developing future face masks that avoid bruising from prolonged use. Most recommendations point dentists to using KN95. However, when combined with respiratory masks, such as the prototype developed in this work, sealed disposable surgical masks are affordable, easy to use, and provide the necessary protection. This study shows the potential of using an air curtain with a face shield for personal respiratory protection. The design of the first functional prototype using CFD modeling was a complex and time-consuming process within the scope of an intensive one-year research and development project, leaving space for deeper studies and with improved experimental and CFD methodologies. The ongoing investigation targets the overall optimization of the developed PPE prototype and is addressed to study the influences of several factors on the protection efficiency, like the human breathing, ambient airflow, user movement and human thermal plume by carrying out usability and reliability tests and CFD optimizations. Furthermore, performing tests in the real environment of a clinic, and simulating a dental treatment, will allow us to understand the complexity of using this PPE for a prolonged time.

**AUTHORS CONTRIBUTIONS**

Nuno Rosa contributed to methodology, investigation, and writing—original draft. Mário Jordão validated and investigated the study and contributed to writing—original draft preparation. José Costa conceptualized the study, supervised the study, and contributed to writing—review and editing. Adélio Gaspar contributed to supervision and writing—review and editing. Nuno Martinho contributed to methodology and writing—review and editing. Miguel Panão contributed to formal analysis and writing—original draft. António Gameiro contributed to writing—review and editing. Manuel Gameiro da Silva contributed to conceptualization, project administration, and funding acquisition.

**ACKNOWLEDGMENT**

The authors thank Nuno Saraiva for his help in the experiments carried out with the particle counters.

**FUNDING INFORMATION**

This work was funded by FEDER—European Regional Development Funds through the COMPETE 2020—Operational Programme for Competitiveness and Internationalization (POCI) in the framework of the project “Mask4MC – mask for medical care” (POCI-01-0287-FEDER-050511) and through the operational program Centro 2020 from Portugal 2020 according to Support System for Scientific and Technological (SAICT) in the framework of the project “VV4MC – A new type of ventilated visor for medical care” (CENTRO-01-0145-FEDER-181248).

**CONFLICT OF INTEREST**

All authors declare that they have no conflicts of interest.

**DATA AVAILABILITY STATEMENT**

The data that support the findings of this study are available from the corresponding author upon reasonable request.
REFERENCES

1. Piret J, Boivin G. Pandemics throughout history. Front Microbiol. 2021;11:631736. doi:10.3389/fmicb.2020.631736
2. Jones KE, Patel NG, Levy MA, et al. Global trends in emerging infectious diseases. Nature. 2008;451:990-993. doi:10.1038/tnature06536
3. Priyadarsini SL, Suresh M, Huisingh D. What can we learn from previous pandemics to reduce the frequency of emerging infectious diseases like COVID-19? Glob. Transitions. 2020;2:202-220. doi:10.1016/j.glt.2020.09.003
4. Fennelly KP. Particle sizes of infectious aerosols: implications for infection control. Lancet Respir Med. 2020;8:914-924. doi:10.1016/s2213-2600(20)30329-4
5. Stadnytskyi V, Anfinrud P, Bax A. Breathing, speaking, coughing or sneezing: what drives transmission of SARS-CoV-2? J Intern Med. 2020;289:1010-1027. doi:10.1111/jim.13326
6. European Centre for Disease Prevention and Control, 2020. Interim Infection Prevention and Control Guidance for Dental Settings During the Coronavirus Disease 2019 (COVID-19) Pandemic. https://www.cdc.gov/coronavirus/2019-ncov/hcp/dental-settings.html (accessed 7.20.21).
7. Ather A, Patel B, Ruparel NB, Diogenes A, Hargreaves KM. Coronavirus disease 19 (COVID-19): Implications for clinical dental care. J Endod. 2020;46:584-595. doi:10.1016/j.joen.2020.03.008
8. Banakar M, Lankarani KB, Jafarpour D, Moayed S, Banakar MH, MohammadSadeghi A. COVID-19 transmission risk in dentistry: a review and protective protocols. BMC Oral Health. 2020;20:1-12. doi:10.1016/cid/ciaa149
9. To KKKW, Tsang OTY, Yip CCY, et al. Consistent detection of 2019 novel coronavirus in saliva. J Clin Infect Dis. 2020;71:841-843. doi:10.1093/cid/ciaa149
10. Abramovitz I, Palmon A, Levy D, et al. Dental care during the coronavirus 2019 (COVID-19) outbreak: operatory considerations and clinical aspects. Quintessence Int (Berl). 2020;51(5):418-429. doi:10.3290/j.qi.a44392
11. Zhang R, Li Y, Zhang AL, Wang Y, Molina MJ. Identifying airborne transmission as the dominant route for the spread of COVID-19. Proc Natl Acad Sci U S A. 2020;117:14857-14863. doi:10.1073/pnas.2009637117
12. Gao Z, Xu Y, Sun C, et al. A systematic review of asymptomatic infections with COVID-19. J Microb Immunol Infect. 2021;54:12-16. doi:10.1016/j.jmii.2020.05.001
13. Sergis A, Wade WG, Gallagher JE, et al. Mechanisms of atomization from rotary dental instruments and its mitigation. J Dent Res. 2021;100:261-267. doi:10.1177/0022034520976444
14. Johnson GR, Morawska L, Ristovski ZD, et al. Modality of human expired aerosol size distributions. J Aerosol Sci. 2011;42:839-851. doi:10.1016/j.jaerosci.2011.07.009
15. Morawska L, Johnson GR, Ristovski ZD, et al. Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities. J Aerosol Sci. 2009;40:256-269. doi:10.1016/j.jaerosci.2008.11.002
16. Offeddu V, Yung CF, Low MSF, Tam CC. Effectiveness of masks and respirators against respiratory infections in healthcare workers: a systematic review and meta-analysis. Clin Infect Dis. 2017;65:1934-1942. doi:10.1093/cid/cix681
17. Patel MD, Rosenstrom E, Ivy JS, et al. Association of Simulated COVID-19 vaccination and nonpharmaceutical interventions with infections, hospitalizations, and mortality. JAMA Netw Open. 2021;4:1-14. doi:10.1001/jamanetworkopen.2021.10782
18. Occupational Safety and Health Administration. 2009. 1910.132 - General requirements. https://www.osha.gov/laws-regulations/regulations/standardnumber/1910/1910.132
19. Atangana E, Atangana A. Facemasks simple but powerful weapons to protect against COVID-19 spread: can they have side effects? Results Phys. 2020;19:103425. doi:10.1016/j.rinp.2020.103425
20. Sterman Y, Tarazi E, Berman O, et al. Safety on demand: a case study for the design and manufacturing-on-demand of personal protective equipment for healthcare workers during the COVID-19 pandemic. Safety Science. 2021;136:105162. doi:10.1016/j.ssci.2021.105162
21. Wendling JM, Fabacher T, Pèbaï PP, Cosperec I, Rochy M. Experimental efficacy of the face shield and the mask against emitted and potentially received particles. Int J Environ Res Public Health. 2018;18:1-18. doi:10.3390/ijerph18041942
22. Lindsay WG, Noti JD, Blachere FM, Szalajda JV, Beezhold DH. Efficacy of face shields against cough aerosol droplets from a cough simulator. J Occup Environ Hyg. 2014;11:509-518. doi:10.1080/159624.2013.877591
23. Stadnytskyi V, Bax CE, Bax A, Anfinrud P. The airborne lifetime of small speech droplets and their potential importance in SARS-CoV-2 transmission. Proc Natl Acad Sci. 2020;117(22):11875-11877.
24. Pan J, Harb C, Leng W, Marr LC. Inward and outward effectiveness of cloth masks, a surgical mask, and a face shield. Aerosol Sci Tech. 2021;55:718-733. doi:10.1080/02786826.2021.1890687
25. Sterr CM, Nickel IL, Stranzinger C, Nonnenmacher-Winter CI, Günther F. Medical face masks offer self-protection against aerosols: an evaluation using a practical in vitro approach on a dummy head. PLoS One. 2021;16:1-10. doi:10.1371/journal.pone.0248099
26. Li L, Niu M, Zhu Y. Assessing the effectiveness of using various face coverings to mitigate the transport of airborne particles produced by coughing indoors. Aerosol Sci Tech. 2020;55:332-339. doi:10.1080/02786826.2020.18464679
27. Lindsay WG, Blachere FM, Law BF, Beezhold DH, Noti JD. Efficacy of face masks, neck gaiters and face shields for reducing the expulsion of simulated cough-generated aerosols. Aerosol Sci Tech. 2021;55:449-457. doi:10.1080/02786826.2020.1862409
28. Ronen A, Rotter H, Eliash S, et al. Investigation of the protection efficacy of face shields against aerosol cough droplets. J Occup Environ Hyg. 2021;18:72-83. doi:10.1080/15459624.2021.1054067
29. Ueki H, Furusawa Y, Iwatsuki-Horimoto K, et al. Effectiveness of Face Masks in Preventing Airborne Transmission of SARS-CoV-2. mSphere. 2020;5:e00637-e00620. doi:10.1128/msphere.00637-20
30. Sakharov AS, Zhukov K. Study of an air curtain in the context of individual protection from exposure to coronavirus (SARS-CoV-2) contained in cough-generated fluid particles. Physics. 2020;2:340-351. doi:10.3390/physics2030018
31. Herek Clack. 2020. Personal Cold Plasma `Air Curtain’ Design for COVID-19 Protection Moves Forward. Univ. Michigan. URL: https://news.umich.edu/personal-cold-plasma-air-curtain-design-for-covid-19-protection-moves-forward
32. Pais, J.; Jesus, L.; Silva, H.; Lopes, A.; Ramos, J.; Costa, J. J.; Gameiro da Silva, M.; Martinho, N.; Rosa, N.; Matos, S.; Gaspar, A. R.; Viseira de vedaçã aerodinâmica. Modelo de utilidade
como EPI de categoria III, Ref. DP/02/2021/76885. Desenvolvido no âmbito do projeto Mask4MC – Mask for Medical Care (Dispositivo de proteção individual para cuidados médicos), projeto em copromoção liderado pela SETsa - Sociedade de Engenharia e Transformação S.A. e tendo com copromotores a ADAI - Associação para o Desenvolvimento da Aerodinâmica Industrial e a FMUC - Faculdade de Medicina da Universidade de Coimbra.

33. Martinho N, Gameiro da Silva M, Ramos J. Evaluation of thermal comfort in a vehicle cabin. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automotive Engineering*. 2004;218:159-166. doi:10.1243/095440704772913936

34. EN14683:2019+AC. 2019. EN 14683:2019+AC:2019 Medical face masks - Requirements and test methods 26.

35. Forouzandeh P, O'Dowd K, Pillai SC. Face masks and respirators in the fight against the COVID-19 pandemic: an overview of the standards and testing methods. *Saf Sci*. 2021;133:104995. doi:10.1016/j.ssci.2020.104995

36. Liu Y, Ning Z, Chen Y, et al. Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals. *Nature*. 2020;582(7813):557-560.

37. Arellano-Cotrina JJ, Marengo-Coronel N, Atoche-Socola KJ, Peña-Soto C, Arriola-Guillén LE. Effectiveness and recommendations for the use of dental masks in the prevention of COVID-19: a literature review. *Disaster Med Public Health Prep*. 2020;15:1-6.

38. Darwish S, El-Boghdady K, Edney C, Babbar A, Shembesh T. Respiratory protection in dentistry. *Br Dent J*. 2021;230(4):207-214.

How to cite this article: Rosa N, Jordão M, Costa J, et al. Experimental and numerical evaluation of a new visor concept with aerodynamic sealing to protect medical professionals from contaminated droplets and aerosols. *Indoor Air*. 2022;32:e13114. doi: [10.1111/ina.13114](https://doi.org/10.1111/ina.13114)