Postprint of: Tretiakov D., Tesch K., Skorek A.: Mitigation effect of face shield to reduce SARS-CoV-2 airborne transmission risk: Preliminary simulations based on computed tomography, ENVIRONMENTAL RESEARCH, Vol. 198 (2021), 111229, DOI: 10.1016/j.envres.2021.111229

Title: Mitigation effect of face shield to reduce SARS-CoV-2 airborne transmission risk: preliminary simulations based on computed tomography.

Running title: Numerical analysis of the SARS-CoV-2 airborne transmission

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Mitigation effect of face shield to reduce SARS-CoV-2 airborne transmission risk: Preliminary Simulations based on Computed Tomography.

Abstract

We aimed to develop a model to quantitatively assess the potential effectiveness of face shield (visor) in reducing airborne transmission risk of the novel coronavirus SARS-CoV-2 during the current COVID-19 pandemic using the computational fluid dynamics (CFD) method. The studies with and without face shield in both an infected and healthy person have been considered in indoor environment simulation. In addition to the influence of the face shield and the synchronization of the breathing process while using the device, we also simulated the effect of small air movements on the SARS-CoV-2 infection rate (outdoor environment simulation). The contact with infectious particles in the case without a face shield was 12-20 seconds (s), in the presence of at least one person who was positive for SARS-CoV-2. If the infected person wore a face shield, no contact with contaminated air was observed during the entire simulation time (80 s). The time of contact with contaminated air (infection time) decreases to about 11 s when the surrounding air is still and begins to move at a low speed. Qualitative differences between simulations performed on the patients with and without the face shield are clearly visible. The maximum prevention of contagion is probably a consequence of wearing a face shield by an infected person. Our results suggest that it is possible to determine contact with air contaminated by SARS-CoV-2 using the CFD method under realistic conditions for virtually any situation and configuration. The proposed method is probably the fastest and most reliable among those based on CFD-based techniques.

Keywords

COVID-19, 3D-model, airflow, face shield, computed tomography, computational fluid dynamics (CFD)

Funding

This research was supported by departmental funding of the Faculty of Medicine (Medical University of Gdańsk) and Faculty of Mechanical Engineering (Gdańsk University of Technology).

Introduction

Social isolation and personal protective equipment (PPE) have been recommended and used for a long time in the fight against infections. The effectiveness of these methods mainly depends on the infectious agent. In 2019/2020, humanity has met a novel type of cronavirus, the SARS-CoV-2 [1]. The above-described methods and strict hand hygiene were proven to be still valid in reducing the spread of this infection [2,3]. However, in the 21st century, it is impossible to completely isolate people, leading to potentially serious social, economic and political consequences. There are several routes of SARS-CoV-2 virus transmission: airborne, droplet and fomite [1,4–8]. The issue of what distance should be kept between people remains controversial. The World Health Organization (WHO) recommends keeping a distance of at least 1 m from each other during the COVID lockdown, although the large droplets can travel as far as 8 m [6,9,10]. This fact suggests that the use of goggles, face shield and face masks in combination with maintaining distance could contribute to a significant reduction of SARS-CoV-2 spread in the environment.

In the 20th century, a large variety of face masks appeared on the market, e.g., respirator mask, surgical or "medical" mask, dust mask, valve, and non-valve respirators, single-layer face mask. Due to lack of standardization, each country has its own certification standard for each type of face mask. Despite the lack of evidence of face masks' effectiveness in preventing viral infection, pandemic strategies in many countries include recommendations to wear face masks in public places [11–14]. According to Yan et al., wearing a face mask by 50% of the general public reduces infections by 50%. Moreover, the use of a face mask by 80% of people in the community can make the risk of disease transmission very low [15].

One of the crucial arguments being made about SARS-CoV-2 is that there are significant gaps in our knowledge of the new virus and we need to fill them. There are significant limits to all the studies looking at or involving social distancing and personal protective equipment. There are no essential epidemiological studies and randomized control trials. We aimed at developing a model to quantitatively assess the potential effectiveness of face shield in reducing airborne transmission risk of the novel coronavirus SARS-CoV-2 during the current COVID-19 pandemic. Computational fluid dynamics (CFD) is a well-established method for predicting fluid flow in various engineering problems. We believe that this method can provide relevant information to test the distribution of exhaled air, virus transmission, locations, and durations issues.

Materials and Methods

3D model

The head and neck 3D model used to simulate the air flows was downloaded from the Embodi3D.com platform, which was error-free and ready for 3D printing output model (https://www.embodi3d.com/files/file/31130-skin-stl-stl-file-processed/) [16].

Flow modeling: Governing equations

A multi-component and incompressible flow without mass and heat transfer was simulated by the VOF (Volume of Fluid) method [17,18], where surface tensions were neglected. It means that both components share the same velocity and pressure fields. The SARS-CoV-2 airborne transmission was simulated through the volume fraction additional transport equation. Also, a constant density without additional mass sources was assumed. The time-averaged form of governing equations was considered using the RAS (Raynolds-Average Simulation) approach to turbulence modeling [19]. The two additional equations are those of the k-ϖ the shear stress transport (SST) model [20]. It means that both components share the same velocity and pressure fields.

Discretization

The governing equations were discretized utilizing the finite volume method and the corresponding algebraic equation systems were solved using the open-source software OpenFOAM [22]. Convections and diffusive schemes involve Gauss integration. The discretized terms were interpolated using a linear upwind interpolation except for the terms involving volume fractions α, where the van Leer limiter was applied instead. As for the discretized diffusive terms involving normal surface gradients, schemes with limited non-orthogonal correction were considered. Finally, the time scheme is the Crank-Nicolson implicit scheme with the off-centering coefficient 0.9. The fully centered Crank-Nicolson scheme is often unstable for complex geometries and requires stabilization utilizing the "off-centering" technique. The off-centering coefficient of 0.9 is typical for a range of cases and at the same time provides similar accuracy and stability to the backward scheme while needing only one old-time value.

The transient governing equations were solved using the Pressure-Implicit with Splitting of Operators (PISO) algorithm [23]. The pressure equation was solved through the generalized geometric-algebraic multi-grid solver with the combined diagonal-based incomplete Cholesky plus Gauss-Seidel smoother. For the volume fraction, smooth solvers with symmetric Gauss-Seidel smoother were utilized. Under-relaxation factors were set to 1.

Flow domain and boundary conditions

The flow domain consists of the head and neck of the human body, which was placed in a rectangular volume of approximately 0.6 × 0.4 × 0.35 m (length × width × height) (Fig. 1). Next, the distance between the tips of the noses is about 0.14 m. In the second version of the geometry, one of the individuals was wearing a face shield. The walls surrounding the flow volume were regarded as outlets where the atmospheric pressure is constant. Furthermore, the body surface of the individuals was treated as a non-slip wall. Finally, the individuals' nostrils were taken as air inlets to the flow domain, namely the model on the left side of figure 1 inhales and exhales infected air, and the model on the right exhales and inhales clean air. The volumetric flow rate $\dot{V}$ is defined by the following relationship [24]:

$$\dot{V} = A \sin 2\pi t T^{-1} \qquad (1)$$

Two scenarios can be considered. In the first, both people breathed synchronously, for $\dot{V}$, according to equation (1). Whereas in the second, they breathed asynchronously, meaning that the first mode's inhalation coincided with the second model's exhalation, i.e., for $\dot{V}$, according to (1).

Figure 1.

Results

The indoor and the outdoor environment simulation results were presented in Figures 2 and 3. The indoor simulation shows the influence of the face shield and the synchronization of the breathing cycles. In contrast, the outdoor simulation illustrates the effect of a slight air movement on the viral particle spread.

The time of the viral particle spread was reduced to about 12 seconds (s) with asynchronous breathing. If the infected person wore a face shield, no contact with contaminated air was observed during the entire simulation time of 80 s. When the volume fraction of infectious particles in the inhaled air was > 0, it was assumed to be the potential infection moment. Under the considered conditions and in the mutual positioning of people, as in Figure 2, the volume fraction's maximum values reach 4%.

Figure 2.

Figure 3.

Figure 3 shows a comparison of the time of contact with infectious particles (infection time) when the surrounding air is still and begins to move at a low speed of 0.1 m s^{-1}. When air flows towards a healthy person, the infection time decreases to about 11 s. Notably, a much more extensive volume fraction of infected air with infectious particles is visible, which is an order higher than in the case of still air. While in the first case, the maximum values of the coefficient reached 4%, in the second case these values reached as high as 30%.

An example of air movement visualization was shown in Figure 4 after about 30 seconds. This visualization combines the infected air volume fraction α (yellow) and vortices reconstructed utilizing the Q-criterion [24]. The qualitative difference between the case without a face shield (bottom) and when the infected person has a face shield (top) is clearly visible.

Figure 4.

Effects of mesh size and time steps on the results

The effect of the flow domain discretization was shown in Figure 5. Five computational meshes were taken into account. All meshes can be classified as Cartesian (hexahedra dominant). Figure 5 shows the volume fraction of infected air inhaled by a healthy person as a function of time for different mesh sizes ranging from 4.8 to 9.9 $\times 10^6$ nodes. Moving averages of the volume fraction are also superimposed where the time of averaging corresponds to a typical breath period, i.e., 4 seconds. Increasing the number of nodes above 9.2 $\times 10^6$ (i.e., fine mesh; Fig. 6) has a negligible effect on the results. What is more, the onset infection starts at the same time, regardless of the mesh. However, there are differences in the volume fraction coefficient during the simulation: the worse the mesh, the smaller the coefficient values.

Figure 5

Figure 6

Figure 7 shows the influence of the time step on the value of the volume fraction coefficient of infected air inhaled by a healthy person. As before, the onset of infection occurs simultaneously, and the longer the time steps are, the more the initial volume fraction values are over-predicted. The comparison was made for the finest mesh. The computation time for the finest mesh and the shortest time step (0.002 s) was approximately 7 days on two Xeon 5120 2.2 GHz processors (26 out of 28 cores involved). This time was reduced to two and a half days for a time step of 0.006 s with the same computational mesh.

Figure 7.

Discussion

The SARS-CoV-2 virus can be released into the surrounding environment through respiratory emissions and body fluids (saliva). This virus's genetic material was frequently detected in swabs from the throat, conjunctiva, blood, sputum, feces and urine of infected people [25–29]. The most common transmission route is via aerosol (multi-dispersed droplets) excreted from the upper respiratory tract. The airborne aerosol hygiene studies described droplets of airway secretions that evaporate and remain suspended in the airflow or turbulence and can travel distances >1m [30–33]. In our study, numerical analysis of the effect of wearing a face shield on the hypothesized airborne transmission of the SARS-CoV-2 virus was performed using the CFD method. Our study was carried out only on 2 patients, which is a significant limitation. However, it can represent a preliminary model that can be implemented in larger studies. The next study limitation is that we do not consider different sizes of aerosols droplets in expired air.

Watterson introduced the so-called "social distancing" (2m) as a condition for loosening the "lockdown" restrictions. This distance (recommended as >1m (WHO), 1.5m (Northern Ireland), 1.8m (Germany), 6 feet (USA), up to 2m (England, Canada, Spain, Italy) was to help countries return to normal social and economic function [34]. Epidemiologists' recommendations regarding the social distance, wearing face masks and hand disinfection should be contrasted with the increase in the number of cases observed in recent weeks in most European countries (so-called "second wave" of COVID-19 infections). So does a "safe social distance" actually exist? Is it a matter of "when" instead of "if" we become infected? The enormous political pressure to re-open the economy, cultural activity, and schools seem to have not survived the test of time. A separate issue is the concept of "infection," an complicated, multi-factorial process that depends on the pathogen (e.g. its virulence, particle size, penetration depth, the massiveness of contact) and the infected person (e.g. immune status, comorbidities). The term "time of infection" should be supplemented with the term "contact time" with the microorganism [35]. In this sense, both social distance and contact time have two aspects: indoor and outdoor environments.

Indoor

In our study, we demonstrated that while staying in a standard room with an infected person who does not use personal protection equipment (PPE) there is a possibility of infection of a healthy person in a short time (assessed as breathing air containing the virus particles). It depends on the room's volume, temperature, humidity, time spent together, and objects in the room that can modulate the exhaled air direction and virus concentration in the exhaled air [36–38]. In our study, we also paid attention to the type of breathing. In our opinion, asynchronous breathing is identical to the irregularity of exhaling air, e.g. coughing, sneezing, singing, screaming. In our study, spending time with a person who breathes this way can accelerate the time of contact with contaminated air by up to 40% (20 sec. vs. 12 sec.).

Wang et al. emphasize the role of the size of droplets suspended in the exhaled air for the duration of their persistence in the environment and the distance they can travel from an infected person. Large droplets

> 100 μm stay in the space of 10 s and small 5-10 μm even up to 17 minutes [36]. Droplet size also determinee the depth of their penetration in the respiratory system - more massive drops usually settle in the nose, and smaller ones penetrate the lung's inferior part [39]. Besides, the virus's concentration is higher in the smaller droplets [40]. Other authors report that the infectivity of viruses in the exhaled air may persist for up to 16 hours [38]. Asynchronous breathing promotes small or tiny drops, usually from the lower respiratory tract, which can linger longer in the environment and travel a longer distance from the infected person [36,41,42].

Forced air exchange in rooms (e.g., in hospitals) does not remove all virus particles suspended in the air, and viruses can persist in the air inlet/outlet openings even for several days [43]. Many reports of the virus are moving through ventilation ducts between neighboring apartments or restaurants without direct contact with infected people [36]. The situation concerns people who do not use PPE. Watterson emphasizes the role of interpersonal isolation as a factor to end (or to significantly slow down) the pandemic's spread. In the case of staying in closed rooms, it seems that the statement that "the best mask is a distance of 2 meters" is not appropriate [34].

The introduction of air movement to the system we examined, extended the time of contact with contaminated air by about 46% (24 sec. vs. 11 sec.) for the same breathing pattern. The investigated system simulates staying in a shared air-conditioned room while maintaining social distance without the PPE (e.g. restaurant, school, public transport, shopping mall, cinema, hotel, cruise ship, conference room). Moreover, attention should be paid to the almost 8-fold increase (4% vs. 30%) in the air exhaled by a COVID-19 positive in the air inhaled by a healthy person, observed in our research. The experiment demonstrates that the introduction of air conditioning, air purifiers, dust extractors, or other mechanical devices releasing air movement may increase infections among people staying indoors. Our results are consistent with the observations of other authors [37,41,44].

Outdoor

These processes take a different course in open spaces, where the possibility of virus spread is influenced by atmospheric factors (e.g., wind, rainfall). However, it should be remembered that the claim that the virus can spread both by droplets and by air has many supporters. Environmental pollution with dust may persist in the outdoor environment for several weeks [34,45–47]. Social distancing and PPE should also be used outdoors. Its shortening and/or the absence of an PPE, e.g., during demonstrations or sports events, assuming asynchronous breathing conditions, may favor the development of infections, which was confirmed by our research and reports by other authors [40,47].

The observations of Setti et al. on the possibility of creating clusters of SARS-CoV-2 virus with particulate matter (dust) in the external environment are fascinating [45]. It is consistent with the observed increase in cases in some countries (Silesia in Poland, Bavaria in Germany, northern Italy, California) in highly industrialized districts (with atmospheric pollution) compared to a decrease in the number of cases in less populated and less industrialized places [48].

The value of the face shield as PPE.

According to the WHO recommendations and many national epidemiological societies, one of the basic measures to limit virus transmission is to wear a mask or a face shield. Their use has at least two dimensions: qualitative cover (a reduction (e.g., surgical masks) or elimination (PPF-2, -3 masks) of virus spread) and directional cover (elimination or control of possible leaks) [39,40]. In our model the face shield was potentially infected and simply modulated the flow of the exhaled air. We found that in the indoor setting it was effective in both synchronous and asynchronous breathing. The face shield perfectly protects, first of all, the horizontal direction "straight-ahead", and it is dangerous when the infected person using it stands (bends) over the healthy person. When worn by an infected person, the face shield protects the environment however it does not protect the healthy person in any way. Thus, medical staff should contact people with COVID (+) or COVID (-) using these safeguards. Moreover, in our study we did not observe any redirection of the exhaled air stream towards the back, coronary, or sideways, which in reality depends on the head position in relation to the body. Viola et al. also raise the problem of the accuracy of wearing the masks (covering both the nose and mouth) and the fact that coughing or sneezing may "detach" the mask from the face, causing it to leak [39].

Conclusions

It is possible to determine the time of contact with contaminated air utilizing CFD methods under realistic conditions for virtually any situation and configuration. When not wearing a face shield, contact with contaminated air was 12-20 s., in the presence of at least one COVID-19 positive person. If the infected person was wearing a face shield, no contact with contaminated air was observed during the entire simulation time (80 s.). The time of contact with contaminated air (infection time) decreases to about 11 s. when the surrounding air is still and begins to move at a low speed. However, a severe limitation is the computation time that requires significant computing power.

Among the many possible models for the process of breathing and movement of air, the model we described seems to be the simplest. This method simulates air that consists of two different components without mass and heat exchange between them. Furthermore, when a healthy person begins to inhale the infected air, it is considered the infection's beginning. It also means that the volume fraction of the infected air inhaled by a healthy person is more significant than zero.

Acknowledgments

Declarations

Funding: This research was supported by departmental funding of the Faculty of Medicine (Medical University of Gdańsk) and Faculty of Mechanical Engineering (Gdańsk University of Technology).

Conflicts of interest/Competing interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the research reported in this article.

Ethical approval: Study protocol was approved by the Regional Bioethics Committee at the Medical University of Gdańsk, Poland (approval nr. NKBBN/521/2013).

Consent to participate: Each patient gave written consent to use his/her CT images in a given research study.

Consent for publication: All authors approved the manuscript and agreed to be accountable for all aspects of this research.

Availability of data and material (data transparency): Not applicable

Code availability (software application or custom code): Not applicable

Author contributions:

Dmitry Tretiakow: Conceptualization; Data curation; Formal analysis; Methodology; Project administration; Supervision; Validation; Visualization; Writing - original draft

Krzysztof Tesch: Data curation; Formal analysis; Investigation; Methodology; Resources; Software; Validation; Visualization; Writing - original draft.

Andrzej Skorek: Conceptualization; Formal analysis; Project administration; Supervision; Validation; Writing - original draft

Figure and table legends:

Figure 1: Flow domain (inlet and outlet surfaced indicated)

Figure 2. Results: without air movement.

Figure 3. Results: with air movement

Figure 4. Flow visualization

Figure 5. Mesh convergence

Figure 6. Domain discretization

Figure 7. Temporal convergence

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