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Airflow dynamics in an emergency department: A CFD simulation study to analyse COVID-19 dispersion

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Abstract  Emergency departments (EDs) in hospitals are hotspots for highly transmissible infectious diseases and pose the most significant risk of viral infection spreading. With the recent COVID-19 outbreak, it became clear that emergency department design must evolve in order to be adequately prepared to handle the epidemic. The purpose of this research is to examine the design of the emergency department at a university hospital using a computational fluid dynamics (CFD) simulation based on the ANSYS CFX package. Turbulence Kinetic Energy and Velocity profiles were analyzed to determine which areas of the ED were most susceptible to virus spread. The analysis revealed that three critical areas of the emergency department, namely overnight patient beds, operating rooms, and resuscitation rooms, had significantly higher air velocity, dispersion, and mixing levels than the rest of the department’s spaces. According to the two scenarios examined, the possibility of air transmission from these locations to neighboring areas becomes apparent, increasing the likelihood of transmitting the virus from these locations and infecting people in the adjacent areas, including patients and health care providers. Using the results of CFD simulations, a solution in the form of instructions for the arrangement of inlets and outlets, the separation of spaces, and the interior design of the spaces and hallways can be presented to the hospital administration. All of which can be implemented in the current design of the emergency department.

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through knowledge in microbiology and microbial ecology, technology, and Germ theory. Following the Spanish flu outbreak, legislatures and health agencies enacted regulations stipulating the principle of hygiene, social isolation, and other principles of Environmental Controls (ECs) [1]. ECs are based on methods for reducing infectious agent concentrations in the air and on surfaces in indoor environments. World Health Organization (WHO) guidelines also recommend a combination of environmental control mechanisms to avoid the spread of viruses to health care workers (HCWs) and patients in healthcare settings [4]. The Environmental regulations rely on the design of the healthcare environment and include (a) building materials, surfaces, and products used [3]; (b) indoor environmental factors (e.g., temperature, humidity, light, and airflow) [2]; and (c) indoor access to the outside, all of which may influence the survival of microorganisms in the built environment.

Microorganisms can be transmitted via direct or indirect contact with an infected person or a contaminated object or via droplet and airborne transmission. This occurs when respiratory droplets, usually greater than 5 μm in size transmitted from an infected person and travel in the air for distances to reach another person [5]. Airflow and ventilation system play significant role in pathogen transmission [6,7]. The design of a ventilation system depends on the ability to contain, mitigate, and remove airborne pollutants through air change and inward indoor airflow [8]. By creating negative air pressure within the healthcare space, the exhaust rate prevents contaminated air from escaping into other adjacent spaces [9]. Additionally, it is critical to design the ventilation system such that turbulence is eliminated [10]. Studies investigated the location of air inlet and outlet through experimental tests and simulation using advanced programs [11–16]. Such experiments culminated in a series of design codes and standards to legislate a set of minimum requirements for ventilation systems in healthcare environments. For example, the American Society of Heating, Ventilation, Refrigeration, and Air-Conditioning Engineers (ASHRAE) issues a specific standard pertaining to the ventilation of healthcare facilities. ASHRAE’s standard specifies that non-critical patient rooms should receive six air changes per hour (ACH), with a minimum of two of those complete air changes coming from outdoor air brought inside [14]. Air quality and ventilation research centered on individual areas such as isolation quarters [12,13], hospital corridors [16], nursing stations [2], and operating rooms [11] to provide suitable air suppression locations and to ensure that airborne transmissions do not reach users of care areas. Studies that examined the emergency room are few or minimal [15].

Emergency departments (EDs) serve as the entry point for all patients with diseases or injuries, including those with emerging and reemerging infectious diseases. EDs experienced a 20% decrease in patient numbers in the COVID-19 outbreak compared to the same timeframe in the prior year [17,18]. The incidence of cardiac arrest rose by more than 45%, suggesting that patients with medical emergencies are avoiding the ED due to fear of contracting COVID-19. The presence of health care workers (HCWs) in emergency departments also place them at greater risk of COVID-19 infection because the majority of patients with infectious diseases are not diagnosed prior to admission [19]. EDs design and spatial arrangement pose similar cross-infection risk for patients and HCWs [19]. ED is functionally split into separate areas, including patient waiting area, triage, resuscitation area, minor procedure rooms, major operating room, medical services, consultation rooms, and observation units [20]. Patient’s movements between those spaces raise the probability of virus transmission to HCWs and other patients. Patients’ and HCWs’ movements have an influence on airflow patterns. Cross-infection between occupants of various spaces in the ED is possible due to air mixing. Thus, a proper spatial arrangement and ventilation system contributes to mitigating or controlling the transmission of viruses within it.

Infection prevention is essential for any health facility. Therefore, this research focuses on evaluating the design of an existing emergency department and investigates intra-department airflow patterns and their relationship to the department spatial layout to identify risk locations for both staff and patients. It provides recommendations for hospital administration to improve the existing ED design. This, in essence, would lead to a reduction in the workload of hospitals, enabling them to maintain the highest number of employees without being compromised by the risk of spreading diseases between them, which will allow the hospital to operate at full capacity.

2. Material and method

2.1. Case description

Fig. 1 depicts the layout and geometry of the emergency department of King Abdullah University Hospital (KAUH). The department has a total floor area of approximately 740 m², and its volume is around 2011 m³. The ED consists of a waiting hall, resuscitation room, surgical cubicle, treatment cubicle, operating rooms, staff rooms, overnight patients’ beds, and service rooms. The department is primarily mechanically ventilated. The 3D CAD model of the ED was created using technical drawings from the university’s Engineering Projects Department. Fluid (in this case, air) volume is generated from the 2D drawings to generate the grid for the CFD simulation.

The HVAC system is comprised of a set of inlet and outlet grilles installed in the room’s ceiling at heights of 2.70 m and
2.40. The total airflow rate is 11,500 m³/h, and the system works with a 100% fresh air supply. The HVAC system was examined in operation conditions at temperatures of 24–26 °C and relative humidity of 30 and 60%.

In the case of an epidemic, the ambulance and emergency department may have a high volume of equipment and users, resulting in alterations in airflow. Thus, air movement in the emergency department was examined in the absence of persons or equipment and in the presence of equipment and users. The placements of the medical equipment were identified using the hospital's and engineering project's unit's technical drawings. A field visit to the emergency department validated the distribution of furniture and equipment. Patients and health care providers are the department’s users. The department’s maximum capacity is 20 patients at a time, while the department’s usual occupancy rate is less than 52% [21]. Nurses, nursing assistants, paramedics, residents, medical experts, therapists, and technicians comprise the medical personnel. As a result, the movement of health care professionals was investigated using health care protocols and the DepthMap software [22] to ascertain the movement and its locations, as seen in the density heat map in Fig. 2. The users and their locations were represented in the model by a cuboid with a height of 1.70 cm and dispersed according to the density seen in the Fig. 2. Outside the unit, in the exterior waiting area, patients and escorts were excluded from the model.

2.2. Cfd setup

The CFD simulation is based on utilizing the CFX package of ANSYS 2020 [23]. Once the building geometry has been modeled, it has been imported to ANSYS. The model has been developed using the Boolean technique (i.e., the solid domain is subtracted from the fluid domain). Essentially, the usage of this technique is justified for aerodynamic or fluid dynamic analyses [24]; thus, it has been adopted herein for this paper. The mesh of the model has been generated using approximately 16 × 10⁶ elements, as shown in Fig. 3.

Fig. 1 The geometry of the Emergency Department.

Fig. 2 Furniture arrangement and movement heat map.
The number of elements has been chosen after performing mesh sensitivity analysis to ensure the independence of the results on the mesh size, Fig. 4. The mesh sensitivity analysis has been performed with respect to average velocity over a plane with an offset of 1.7 m from the floor, which is approximately the average person’s height in the Middle East Region [25]. As shown in Fig. 4, the results become insensitive of the mesh size approximately at $1.4 \times 10^6$ elements. Therefore, any mesh size greater than $1.4 \times 10^6$ is justified to ensure the results’ independence of the mesh size. To provide a higher level of certainty, a mesh size of $16 \times 10^6$ elements have been chosen for the simulation.

Furthermore, the mesh quality (Table 1) is within the conventional standard values for similar study cases [26–29]. Once the mesh has been generated, it has been exported to the CFX-PRE to define the required setup, corresponding to the case of the study.

**Table 1** Mesh properties.

| Property                        | Value       |
|---------------------------------|-------------|
| Elements maximum size (mm)      | 100         |
| Number of elements              | $16 \times 10^6$ |
| Growth rate                     | 1.2         |
| Defeature size (mm)             | 0.5         |
| Curvature minimum size (mm)     | 1           |
| Curvature normal angle (degree) | 18          |
| Skewness                        | 0.8         |
| Inflation transition ratio      | 0.75        |
| Inflation number of layers      | 5           |

Fig. 3 CFX mesh of the model.

Fig. 4 Mesh sensitivity analyses with respect to the average velocity at 1.7 m offset.

Fig. 5 Convergence results.
The analysis type has been defined as a steady-state with the k-Epsilon model. The fluid domain has been defined as 'Air at 25°C' from the ANSYS models library. The solid domains of the model have been defined as 'No Slip Walls.' It shall be highlighted that this study aims to analyze the worst-case scenario of the COVID-19 spread, which essentially, according to the World Health Organization (WHO), becomes more severe in closed areas [30]. Therefore, this simulation has been performed assuming closed entrances have been defined as 'No Slip Walls.'

Finally, the inlet boundary conditions have been all specified as velocity inlets with the default turbulence intensity of 5%. In contrast, the outlet boundary conditions have all been defined as pressure outlets at 0.85 bar, which correspond to the suction condition. As shown in Fig. 5, the model has converged with residual targets of $1 \times 10^{-3}$.

As reported in the literature [31–33], the Turbulence Kinetic Energy ($k$) is utilized to describe the flow mixing level. Since this study aims to assess the level of COVID-19 spread which is highly dependent on the level of the flow mixing, the Turbulence Kinetic Energy ($k$) has been adopted as a determinate parameter for this paper. The Turbulence Kinetic Energy ($k$) is plotted in ANSYS CFX using Equations (1–4) [31–33].

$$k = \frac{3}{2} (Uj)^2 \quad (1)$$

$$\varepsilon = c_f k^{3/2} \quad (2)$$
\[ I = 0.16Re^{-\frac{1}{2}} \] \hspace{1cm} (3) \\
\[ I = 0.07L \] \hspace{1cm} (4)

Results have been plotted for the entire fluid domain as 3D streamlines. In addition, as shown in Fig. 6, results have been plotted at two different planes; the first is at 1.7 m above floor (i.e., the average person height in the Middle East Region [25]). The second is at 1 m above the floor, which approximately corresponds to the height of medical benches.

3. Results

3.1. Velocity profiles

Figs. 7 and 8 shows the velocity profiles over the two planes (1.7 m and 1 m above the floor). As shown in Figs. 7A and 8A, the velocity magnitude at 1.7 m above the floor is approximately within the interval (0.1–0.25) m/s. However, at both entrances (Region 1 and 3), air velocities are recorded at their lowest levels, thus eliminating the influence of the velocity factor for COVID-19 transmission from those areas to neighboring areas. It can also be noted that the flow through the aisles (a, b, and c) generally has not gained significant additional kinetic energies ($\frac{1}{2}mv^2$) from the primary sections of the building (i.e., patients section, physician section, and operating section) as the velocities at those aisles maintained approximately a consistent profile and were not influenced by velocity profiles of the primary sections. However, the same cannot be said about the aisle in Region 2. The kinetic energy at this region was influenced by the velocity streamlines from the patients’ section to the physician section. Therefore, since kinetic energy, by definition is the ability of particles to be moved from one place to another, then the spread of COVID-19 at this region is more likely to happen. The reason for highlighting this region is the low level of people’s expectation of airflow to be transferred from one section to another (i.e., patients section, physician section), which could increase the risk of transmitting COVID-19.

As shown in Fig. 7B and 8B, the velocity profile of the 1 m plane approximately followed the same pattern as the 1.7 m plane. Nevertheless, by comparing region 4 of the 1 m plane to region 3 of the 1.7 m plane, it can be seen that the velocity has slightly increased as it was influenced by the patients’ section. However, any minor increase in velocity at this height could be potentially critical as this plane (1m above the floor) corresponds to the height of medical benches (i.e., patients’ breathing level) or kids heights; thus, it is preferable to
maintain velocities at a minimal level to decrease the airflows' kinetic energy which as a result reduces airborne dispersion of droplets to neighboring sections.

By comparing the velocity profiles in both cases with and without the presence of equipment and people, it can be noticed that the velocity increased slightly when equipment and people were present, as it was more affected in the patients' section and surgical cubicles, as shown in Fig. 8.B at a height of one meter above the ground. As a result, the probability of the virus spreading from these regions 5 and 6 to surrounding areas or inside them is likely to grow.

3.2. Turbulence kinetic energy profiles.

As discussed in section 1, the importance of plotting the turbulence kinetic energy appears in highlighting the region of high dispersion and mixing levels, which corresponds to the regions in which COVID-19 is more likely to be spread compared to other regions. As shown in Figs. 9 and 10, the relatively higher flow dispersion and mixing levels are focused in regions 7, 8, 9, and 10 of the operating rooms and patients section, compared to other sections. However, it is remarkable that the dispersion and mixing profiles (i.e., turbulence kinetic energy profiles) are contained within each section and not transferred from one section to another, thus reducing the likelihood of spreading COVID-19 from one region to another. It can be noted that the regions with relatively high levels of turbulence kinetic energy profiles at the 1 m floor (regions 9 and 10) are more extensive than those at 1.7 m (regions 7 and 8), thus highlighting a higher probability level of flow dispersion at the height of medical benches (i.e., patients' breathing level). This also means that the transmission of COVID-19 is more likely to occur amongst lying down patients than standing personnel. However, since regions 9 and 10 correspond to an aisle, walking personnel are exposed to a higher level of risk at those regions than other regions as shown in Fig. 10.B. It is also worth noting, as mentioned in Section 1, the impact of medical equipment on air velocity and turbulent kinetic energy profiles in surgical cubicles—region 11, which contributes to the virus’s further dissemination among patients and healthcare providers inside this region.

3.3. Airflow streamlines

The significance of plotting the velocity streamlines appears in precisely identifying the sources (flow inlets) and destinations...
(flow outlets) of air particles, thus; highlighting how airflow may or may not be transferred from one section to another. It also identifies the suction capability of each section, such as whether airflow leaves the building from its designated outlet (within the same section) or is forced to leave from other outlets (at other sections), thus increasing flow transmission through sections. Figs. 11 and 12 (B, D, E, F, and G) show the velocity streamlines from the velocity inlets of 1.05 m/s, 0.62 m/s, 0.59 m/s, 0.52 m/s and 0.42 m/s, respectively. It can be generally said that the airflow from those inlets leaves the building from its designated outlets (i.e., within the same section as the inlet). At the same time, only a relatively negligible amount of air escapes to other sections at low velocities (i.e., approximately 0.05 m/s-0.001 m/s). Therefore, the velocity level at those inlets (0.62 m/s, 0.59 m/s, 0.52 m/s, and 0.42 m/s) could be considered well-balanced with their suction levels designated outlets.

On the other hand, it can be seen that the suction level at the patients’ section (Figs. 11.C and 12C) is less sufficient compared to the other sections of the building. Therefore, the flow is forced to escape from other outlets (i.e., through the physician section). This, as a result, increases the likelihood of transmitting COVID-19 from the patients’ section to the physicians, compared to other sections. Therefore, it is recommended to decrease the suction level at the physician section and increase it in the patients’ section. Alternatively, the airflow rates at the patients’ section shall be reduced while maintaining an acceptable level of air conditioning (cooling/heating).

4. Discussion

By plotting the velocity profiles, it was found that both entrances’ velocities are recorded at their minimal levels, thus eliminating the velocity factor of increasing the spread of COVID-19 at those regions. Moreover, the flow through the aisles (a, b, and c) generally maintained approximately a consistent profile and were not influenced by velocity profiles of the primary sections, which shows that no additional kinetic energy was gained from the primary sections (patients section, operating section, and physicians section), thus; at those aisles, COVID 19 is less likely to be transferred. However, for other aisles, higher levels of velocity were spotted.

By plotting the turbulence kinetic energy appears, the region of high dispersion and mixing levels has been spotted, which correspond to the regions in which COVID-19 is more likely to be spread than other regions. Those were identified as the operating and the patients’ section. Remarkably, the

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**Fig. 10** Turbulence kinetic energy profiles with people and equipment.
turbulence level was determined to be at higher levels at the 1 m above the floor, which corresponds to the height of medical benches (i.e., patients’ breathing level). This also means that the transmission of COVID 19 is more likely to occur amongst lying down patients than standing up personnel at the patients’ section.

By plotting velocity streamlines, it was found airflow from the patients’ section escapes to the physician section. Therefore, it was recommended to decrease the suction level at the physician section and increase it in the patients’ section. Alternatively, the airflow velocity could be reduced in the patients’ section while considering other parameters (i.e., temperature) to sustain an acceptable air conditioning level.

Comparing the airflow in both situations with and without equipment and users reveals a small increase in airflow when equipment and people are present.

Finally, it shall be explicitly highlighted that the results of this paper are relative but not absolute, such that regions that were identified as high/low-risk regions are in comparison to the other areas of the building.

Fig. 11  Velocity streamlines from all inlets, building without people or equipment.
5. Conclusions

In the context of COVID-19, the goal should be to contain and prevent the virus's transmission to the greatest extent possible. It is critical to keep the risk of airborne infection transmission to a minimum in the hospital emergency department to protect patients and health care workers while also flattening the COVID-19 curve.

This investigation was conducted to gain a better understanding of the airflow patterns in the emergency department at King Abdullah University Hospital. The purpose of this study was to examine the performance of the mechanical ventilation system with respect to the spread of the COVID-19 virus throughout the ED's spaces. To investigate the turbulent kinetic energy and flow dynamics, a CFD analysis was performed. The steady-state with the k-ε model is used in this study to numerically model the air flows. The analysis reveals that the highly turbulent fields generated inside patient recovery beds and operating rooms may contribute to the spread of the COVID-19 virus into adjacent spaces. Thus, based on the tested scenario, it is recommended to separate the high-risk areas by using doors or partitions and reconsider the location of inlets and outlets. Relocating inlets and outlets, as it was revealed that the presence of only air outlets in the healthcare providers' area resulted in the withdrawal of air from neighboring spaces. Aisles design also contributes to virus containment. As revealed by the analysis, the aisles contributed to the distribution of air throughout the emergency department. Nearly all hospitals are attempting to safely introduce measures to handle their facilities' increased demand; thus, this study provides hospitals with design guidelines to help tackle the spread of infection. A hospital facility built to promote infection prevention makes healthcare providers' tasks smoother and more effective by reducing stress associated with an elevated risk of infection when operating in the emergency department. Providing accommodating layout quality will significantly improve employee comfort and activity. On the other hand, successful infection prevention strategies can eliminate patient-to-patient infection transactions.

Fig. 12 Velocity streamlines from all inlets, building with people and equipment.
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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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