Numerical Simulation of Particle Dispersion in an Operating Room: Assessment using Horizontal Air Supply Diffuser

Tan, Huiyi
School of Chemical & Energy Engineering, Faculty of Engineering,Universiti Teknologi Malaysia

Keng Yinn Wong
School of Mechanical Engineering, Faculty of EngineeringUniversiti Teknologi Malaysia

Wah Yen Tey
Faculty of Engineering, Technology & Built Environment,UCSI University

Bemgba Bevan Nyakuma
Department of Chemistry, Faculty of Sciences, Benue State University

他

https://doi.org/10.5109/7183456

出版情報：Evergreen. 11 (2), pp.1412-1418, 2024-06. 九州大学グリーンテクノロジー研究教育センター
バージョン：

Numerical Simulation of Particle Dispersion in an Operating Room: Assessment using Horizontal Air Supply Diffuser

Huiyi Tan[1], Keng Yinn Wong[2,*], Wah Yen Tey[3], Bemgba Bevan Nyakuma[4], Chew Tin Lee[1], Syie Luing Wong[5], Mohd Hafiz Dzarfan Othman[6], Hong Yee Kek[2], Natalie Vanessa Boyou[7], Xinyou Ho[1], Wen Tong Chong[8], Haslinda Mohamed Kamar[2], Muhd Suhaimi Deris[9]

[1] School of Chemical & Energy Engineering, Faculty of Engineering,Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia.

[2] School of Mechanical Engineering, Faculty of EngineeringUniversiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia

[3] Faculty of Engineering, Technology & Built Environment,UCSI University, 56000 Cheras, Kuala Lumpur, Malaysia

[4] Department of Chemistry, Faculty of Sciences, Benue State University, P.M.B 102119 Makurdi, Benue State, Nigeria

[5] Dpto. Matemática Aplicada, Ciencia e Ingeniería de Materiales y Tecnología Electrónica Universidad Rey Juan Carlos, C/ Tulipán s/n, Móstoles Madrid, Spain

[6] Advanced Membrane Technology Research Centre (AMTEC), Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia

[7] School of Engineering,University of Aberdeen, Aberdeen, United Kingdom

[8] Department of Mechanical Engineering, Faculty of Engineering,University of Malaya, 50603 Kuala Lumpur, Malaysia.

[9] Bumimaju MTE Engineering Sdn. Bhd, Taman Pinggiran Putra 43300 Seri Kembangan, Selangor, Malaysia

*Author to whom correspondence should be addressed:
E-mail: kengyinnwong@utm.my

(Received June 15; 2022; Revised March 11, 2024; Accepted June 14, 2024).

Abstract: The airflow distribution plays a crucial role in directing the movement of infectious particles within an operating room (OR). To date, there is a lack of study on the effectiveness of horizontal wall-mounted air supply diffusers in reducing BCPs. This paper aims to investigate the efficacy of both vertical downward (default) and horizontal air supply diffusers in mitigating BCPs within the surgical zone. By utilizing a renormalization group (RNG) k-ε airflow model, the air distribution within the OR was simulated, while the transportation of particles was predicted utilising a Lagrangian technique. Five cases were analyzed, including the vertical air supply diffuser as the baseline case, two-sided wall-mounted diffuser on xy plane (case 2), single-sided wall-mounted diffuser on yz plane (case 3), and single-sided wall-mounted diffuser on xy plane (case 4). The findings indicate that the airflow supplied by all wall-mounted diffusers (case 1 – case 4) failed to minimise the number of particles within the surgical region. However, there was a notable increase in particle settlement on the patient. In cases 1, 2, 3, and 4, the particles adhere on the patient's body surface intensified by 8.5-fold, 2-fold, 13-fold, and 15.5-fold respectively.

Keywords: computational fluid dynamics; particle distribution; horizontal wall-mounted air supply; operating room

1. Introduction

An operating room (OR) is a confined space in a healthcare facility where the surgical procedures are carried out in a hygienic environment [1]. A hygienic environment is typically free from infectious microorganisms due to disinfection, sterilization, and decontamination processes [2]. When the OR is under an "at rest" condition, where the room is absent of occupants, a hygienic environment could be easily maintained. However, when there is an ongoing surgical procedure, the medical staff members continuously emit the bacteria-carrying particles (BCPs) in the OR. Hence, effective ventilation is indispensable for establishing a comfortable and safe indoor environment for its occupants [3]. To ensure a low quantity of BCPs nearby the patient, a proper ventilation strategy that supplies clean air to provide the washing effect towards the BCPs shredded by the occupants is crucial. Elevated levels of BCPs at the surgical site has been reported to increase the tendency of a individual contracting a surgical site infection (SSI).

SSI is characterized by an infection developing either at the site of the surgical incision or within the deeper tissues and organs within a period of 30 days following the procedure [4]. It is the third most common classification of hospital-acquired infection (HAI) [5] that ranks amongst the leading causes of death within the surgical patient population [6]. Studies have reported that SSIs have affected approximately 8 % - 41.7 %, 7 % - 25 % and 6.7 % of the patients undergoing spinal dysraphism [7], colorectal [8], and abdominal [9] surgeries, respectively. As a result, patients incur additional treatment costs of US$ 3,000 to US$ 29,000 per case [10], additional length-of-stay of 9.8 days [11], re-admission cases of 25.2 % [12], and mortality rate of 3 %.

Various pathogenic species such as *Escherichia coli*, *Klebsiella species*, *Staphylococcus aureus* [13], *Pseudomonas aeruginosa* [14, 15] are usually bonded to the particles and present as BCPs in healthcare facilities. In the OR, however, the majority of species that adhere to the BCPs have been identified as *Staphylococcus aureus*, which has an aerodynamic particle size of approximately 1 µm - 10 µm [1]. This species mainly originates from the skin flora of the medical staff members. *Staphylococcus aureus* has been reported as the leading cause of SSI and could initiate a severe infection at the surgical site [16].

Indoor obstacles such as medical staff members and surgical lamps are identified as the main factors that influence the airflow pattern in an OR [1]. These obstacles can easily disrupt the unidirectional airflow provided by the vertical air supply diffuser owing to the temperature differences between the air and the surfaces of obstacles [17]. Kamsah, Kamar, Alhamid and Wong [1] claimed that a temperature difference of 10 °C between the surrounding air and the surface of the occupants would increase the BCPs settlement in the region of the surgery table by 16 %. Similarly, Sadrizadeh and Holmberg [18] claimed that the vertical air supply diffuser could promote the BCPs sedimentation on the patient due to the downward inertial impaction factor. Hence, a study suggested that the horizontal air supply diffuser could be an alternative to the vertical air supply diffuser in an OR [17].

Sadrizadeh, Holmberg and Tammelin [19] and Traversari, Goedhart, Dusseldorp, Bode, Keuning, Pelk and Vos [20] concluded that the horizontal air supply diffuser is a good alternative to the vertical air supply diffuser. The authors further stated that the main advantages of horizontal air supply diffuser are ease of installation and maintenance, less air is needed for circulation, does not require cooling of airflow and modification of the existing lighting system. However, Liu, Wang and Wen [17] stated that horizontal air supply does not necessarily improve the airflow pattern and the removal efficiency of BCPs. The study identified that the positioning of occupants and the layout of the OR are the main criteria that determine the efficiency of horizontal air supply. Ho, Rosario and Rahman [21], however, discovered that the distance between the horizontal air supply and the patient was the main factor that influenced the BCPs removal efficiency. So far, the assessment of the effects of horizontal air supply diffuser on the BCPs are limited albeit with controversial findings. Therefore, the present study investigates the efficacy of horizontal wall-mounted air supply diffuser in decreasing the number of BCPs presence and settlement nearby the surgery region.

2. Method of Examination

2.1 Constructing the 3D Model of an OR

A 3D model of an OR was developed utilizing computer-assisted design (CAD) application. The reliability of CFD and CAD have been proven reliable and utilized in airflow and particle dispersion study [22, 23]. The OR has a geometry of 6.0 m (length) × 5.5 m (width) × 2.5 m (height). The CFD model includes five staff members, a lying-down patient, two medical lamps, a medical instrument table, a surgical table, and medical equipment. The furniture arrangement and the positioning of staff members were obtained from Kamar, Wong and Kamsah [24]. The OR receives clean air from the ceiling-mounted diffusers arranged in a perimeter layout. The purpose of having this layout arrangement is to establish an air shield, aiming to reduce the entry of contaminated air from another region. The air is subsequently extracted via the four air return outlets positioned at each corner of the OR. Clean air is referred to as the air that is free from airborne particles. In an OR, the air diffusers are installed with a high-efficiency particulate air filter, or commonly known as HEPA filter. This filter capable of trapping 99.99 % toward the airborne particles that bigger than 0.3 µm (particle's diameter) [5]. Therefore, it is assumed that the air provided from the diffuser is particle-free. The layout and details of the OR are demonstrated in Fig. 1.

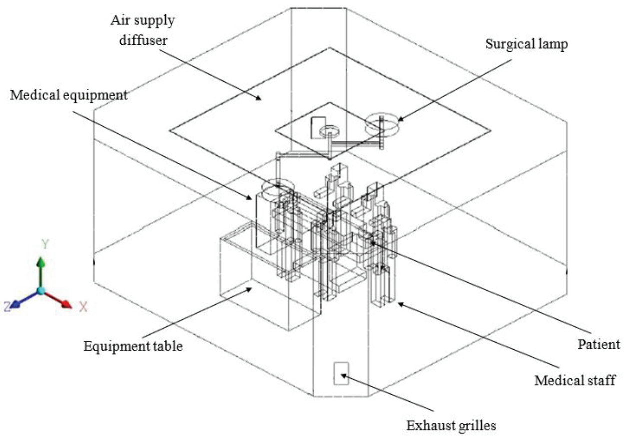

Fig. 1: CFD model of an OR for a baseline case

2.2 Discretizing and Confirming Mesh Independence

Three different types of elements are commonly used in discretizing the CFD model, i.e., hexahedral, tetrahedral, and polyhedral. The use of the tetrahedral element could reduce the mesh non-orthogonality and skewness, and subsequently improve the numerical accuracy at the near-wall region [25]. Likewise, tetrahedral elements are more suitable for the complex geometry of an OR that accommodated the furnish and human manikins [26]. The tetrahedral elements are also stable for steady-state flow analysis [27]. Hence, the tetrahedral element was selected in this study to ensure the reliability of airflow and particle movement prediction in an OR. A grid convergence index (GCI) was determined to identify the appropriate number of elements for the 3D domain. A GCI falls under 5 % signifies that the mesh size is adequately small, resulting in a negligible numerical error the in predicted outcome [28]. The GCI can be calculated via Equation (1) as follows [24]:

$$GCI\ (u) = \frac{F_s \varepsilon_{rms}}{r^p - 1} \qquad (1)$$

where ε_{rms} denotes the relative variance between consequtive solutions, r signifies the ratio of fine elements to coarse elements, F_s denotes the safety factor, set at 3, and p represents the order of convergence, set at 2 [28]. The safety factor Fs is determined through empirical knowledge gained from prior CFD simulations [29]. It signifies a 95% confidence level for the estimated error range [30]. The ε_{rms} can be established using Equation (2) [24].

$$\varepsilon_{rms} = \sqrt{\frac{\sum_{i=1}^{n} \frac{(u_{i,coarse} - u_{i,fine})^2}{u_{i,fine}}}{n}} \qquad (2)$$

where u_i represents velocity of airflow. The present study utilised five different sets of unstructured tetrahedral elements for GCI analysis, range from 380,000 to 6,000,000 elements. The airflow velocities were retrieved from 100 points that were evenly distributed along the x-axis line, connecting the coordinates (0.00, 1.50, 2.75) and (6.00, 1.50, 2.75). The calculated GCIs composing five distinct groups of mesh numbers are illustrated in Fig. 2.

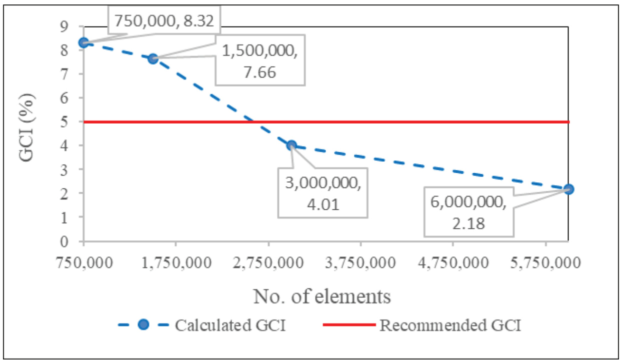

Fig. 2: Variation of GCIs using different sets of elements number

2.3 Applying Boundary Conditions and Specifying Airflow and Particles Properties

The air in the OR is presumed as non-compressible, has a density of 1.204 kg/m^3 and subjected to a gravitational acceleration of 9.81 m/s^2. The study was conducted under a time-independent consideration, wherein the airflow and concentration of BCPs had reached an equilibrium state. An RNG k-ε turbulent model was employed to predict the air distribution, wheareas a discrete particle model (DPM) using the Lagrangian tracking approach was utilised to monitor the BCPs distribution within the OR. The selection of air movement and particle tracking models was based on the extensive validation works in the author's previous publication [24, 31]. Also, the reliability of the airflow model selection has been proven by past studies [32]. Each medical staff member uniformly released the BCP from the body's surfaces at a rate of 600 particles/m^3. Each BCP has a density of 2.0 g/cm^3 [24], with a size of 5 μm in aerodynamic diameter. Brownian motion that considered the random movement of BCPs and thermophoretic force that affected the dispersion of BCPs due to temperature gradient were incorporated into the study. The boundary conditions applied on the 3D model of OR are listed in Table 1.

Table 1. Conditions applied on the 3D model of OR

Item	BCs	Conditions
Air diffuser	Velocity inlet	Velocity: 0.43 m/s Turbulent intensity: 5 % Air temperature: 292 K Discrete phase: Escape
Exhaust grilles	Pressure outlet	Gauge pressure: 0 Pa Discrete phase: Escape
Staff members	Wall	Wall motion: Static wall Heat flux: 116 W/m^2 Discrete phase: 600 particles/ minute
Patient	Wall	Wall condition: Static wall Heat flux: 58 W/m^2 Discrete phase: Trap
Surgical lamps	Wall	Wall condition: Static wall Heat flux: 320 W/m^2 Discrete phase: Trap
Medical instrument/ equipment	Wall	Wall condition: Static wall Heat flux: 255 W/m^2 Discrete phase: Trap
Equipment table	Wall	Wall condition: Static wall Heat flux: 0 W/m^2 Discrete phase: Trap

2.4 Description of Case Studies

In the present study, a cumulative of five scenarios were conducted. One of the case studies is the baseline case that utilized the vertical air supply diffuser, as depicted in Fig. 1. The four remaining case studies utilized different configurations of horizontal air supply diffuser i.e., the two-sided wall-mounted diffuser on yz plane (case 1), a two-sided wall-mounted diffuser on xy plane (case 2), a single-sided wall-mounted diffuser on yz plane (case 3), and single-sided wall-mounted diffuser on xy plane (case 4). Cases 1 - 4 only utilised the horizontal diffusers that were installed on the side walls. All the boundary conditions setups of the diffuser, exhaust grilles, positioning of furnish and medical staff members were identical to default case. For case 1, the air supply diffuser inlets are placed on the x-x planes, plane x = 0 m and plane x = 6 m, while the air supply diffuser in case 2 is placed on the z-z planes, plane z = 0 m and plane z = 5.5 m. The diffuser for case 3 and case 4 only comes from one side of the wall, located on the plane x = 0 m and plane z = 0 m, respectively. The diffuser layout for case 1 - case 4 are depicted in Fig. 3.

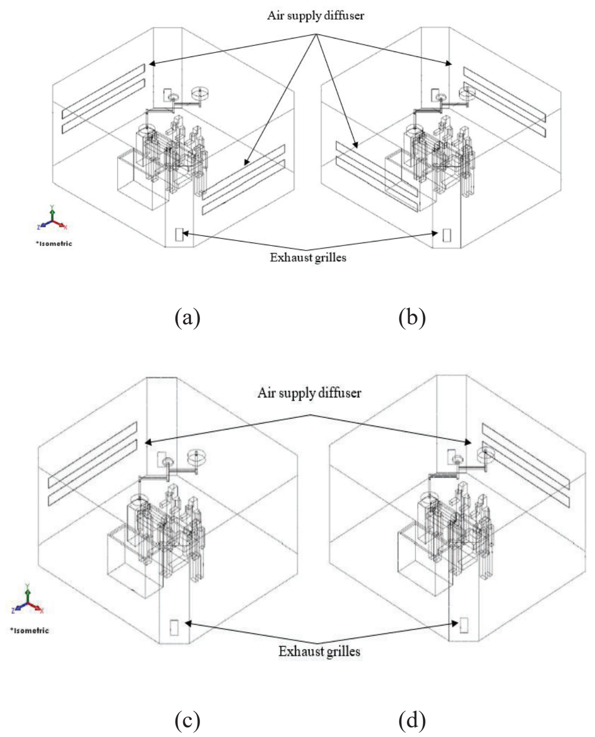

Fig. 3: The horizontal diffuser layout arrangement in the OR of (a) case 1, (b) case 2, (c) case 3, and (d) case 4

3. Results and Discussions

This study highlighted that the airflow condition at the surgical site was highly affected by the large obstacles, i.e., staff members, equipment table and medical instrument. The airflow velocity reduced significantly after passing through the large obstacle. This scenario could lead to poor particle removal efficiency and an increment in the particle's concentration at the stagnant region. Based on the baseline case and all four case studies, stagnant flow can be identified at the region below the operating table with an average velocity of less than 0.01 m/s. Figure 4 shows the air velocity contour on the plane of x = 3.5 for the baseline case and case studies.

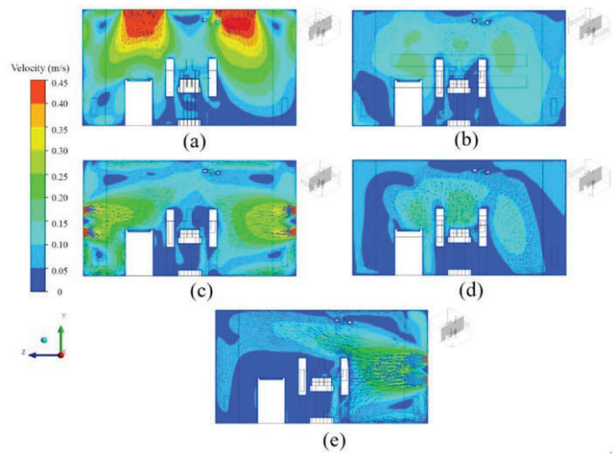

Fig. 4: Air velocity distribution with airflow vector on plane x = 3.5 m for (a) default case, (b) case 1, (c) case 2, (d) case 3, and (e) case 4

According to Fig. 4(a), the clean air was directly supplied from the ceiling-mounted (vertical) diffuser (baseline case) to the patient at the surgical site without facing large obstacles. The small obstruction of the surgical lamp mounting provided a negligible effect on the supplied air. The average air velocity obtained at the surgical site under the vertical air supplied diffuser was approximately 0.11 m/s. In the OR equipped with the two-sided horizontal wall-mounted air supply diffuser demonstrated in Fig. 4(b) and Fig. 4(c), the air distribution at the surgical site depended heavily on the location of obstacles. When the air was directly supplied from the horizontal diffuser to the surgical site as depicted in Fig. 4(b), without passing through the large obstacle, the average airflow velocity at the surgical zone is approximately 0.09 m/s. However, the average air velocity at the surgical zone was further reduced to 0.06 m/s when the air passed through the medical staff members as illustrated in Fig. 4(c). The average air velocity distribution is even lower in case 4 that utilized the single-sided diffuser. An insignificant air velocity condition at the surgical site is not preferable as it might reduce the wiping effect towards the BCPs that are shredded by the staff members. Figure 5 shows the particle distribution contour on plane x = 3.5 m, intersecting two staff members and an equipment table, for both the baseline scenario and case studies.

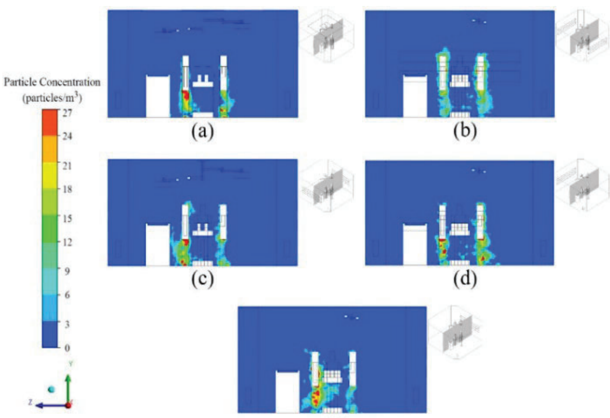

Fig. 5: Particle distribution on plane x = 3.5 m for (a) default case, (b) case 1, (c) case 2, (d) case 3, and (e) case 4

Figure 5 shows the baseline case has the lowest amount of particles dispersed into the vicinity of the patient. Most of the BCPs tended to move down according to the supplied airflow direction. While the horizontal air supply diffuser in cases 1 – 4 promoted more BCPs dispersed into the vicinity of the patient, especially the single-sided horizontal diffuser on the xy plane, as shown in Fig. 5(d). The relatively low velocity of 0.02 m/s in the region nearby the patient has a poor air dilution or washing effect towards the BCPs. Likewise, the stagnant airflow region presented between the medical staff member and equipment table caused the accumulation of BCPs. This scenario could cause the BCPs to settle on the sterile instruments placed on the equipment table [33]. The plan view of particle dispersion contour on the plane of y = 1.15 m for the default case and case 1- case 4 is depicted in Fig. 6.

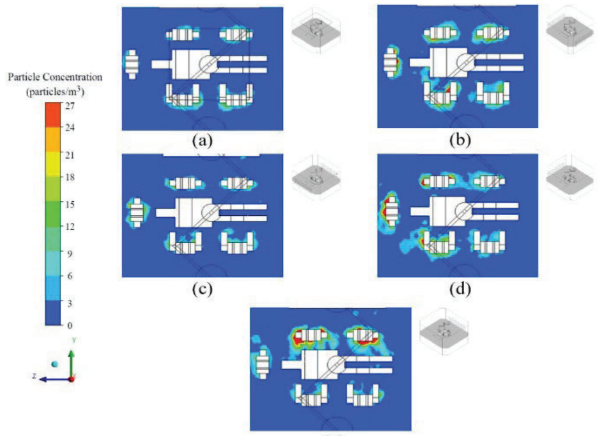

Fig. 6: Particle distribution on plane y = 1.15 m above floor level for (a) default case, (b) case 1, (c) case 2, (d) case 3, and (e) case 4

Based on Fig. 6(a), the OR equipped with the vertical air supply diffuser has maximum BCPs of 13 particles/m^3 gathered at the region around the staff members. Negligible BCPs were transported into the region near the patient due to the vertically descending unidirectional airflow. However, the BCPs surrounded the medical staff members for both cases of double-sided air supply diffusers on plane x-x (Fig. 6(b)) and plane z-z (Fig. 6(c)) was slightly higher, with a highest concentration of 19 particles/m^3 and 24 particles/m^3, respectively. The horizontal air supply diffusers in these two cases are more likely to push the BCPs released by the staff members penetrating the region of surgical zone, instead of diluting the BCPs concentration. The current study highlighted that the single-sided horizontal diffusers in cases 3 and 4 were relatively weak in lowering the particles within the surgical site due to the low airflow velocity in the vicinity of the surgical zone. A noticeable BCPs concentration of 26 particles/m^3, and 27 particles/m^3 were identified on the plane of y = 1.15 m, respectively. The quantity of BCPs adhered on the patient's body surface is shown in Fig. 7.

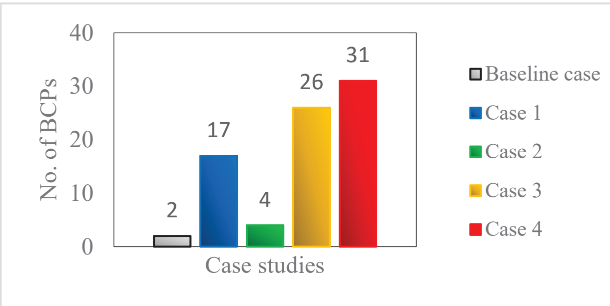

Fig. 7: Quantity of BCPs adhered on a patient's body surface

Figure 7 shows that the OR equipped with a vertical diffuser (baseline case) capable of reducing the BCPs adherence on the patient better than the horizontal wall-mounted diffuser (cases 1 – 4). Only two BCPs settled on the patient under a time-independent airflow scenario. Although the airflow circulation at the surgical region for default case and two-sided horizontal diffuser in case 2 are almost similar, the efficiency of removing of BCPs from the surgical site for case 2 was not as promising as the baseline case. The BCPs settlement in case 2 was two times higher than the baseline case. This scenario indicated that the airflow direction in the vicinity of the patient significantly affected the dispersion and settlement of the BCPs. Among all 5 case studies, the airflow circulation nearby surgical region was found to be low and stagnant in cases 3 and 4. The single-sided air supply diffusers in cases 3 and 4 have resulted in 26 and 31 BCPs adhered on the patient's body surfaces, respectively. The motionless airflow region at the surgical site has caused more BCPs to remain airborne under the effect of Brownian motion force and subsequently adhering to the upper surfaces of the patient due to gravitational acceleration.

4. Conclusion

A CFD method was deployed to simulate the movement of BCPs within the operating room. The study aimed to evaluate the efficacy of both vertical downward (default) and horizontal air supply diffusers in mitigating BCPs within the surgical zone. The air distribution within the OR was simulated by utilizing a RNG k-ε airflow model, while the transportation of particles was predicted utilizing a Lagrangian technique. The present analysis showed that an OR installed with horizontal diffusers failed to minimise the concentration of particles at the critical region of surgery. There was a significant increase in particle settlement on the patient, specifically by 8.5-fold, 2-fold 13-fold and 15.5-fold in case 1, case 2, case 3 and case 4. The highest concentration of particles accumulated around the staff member at the height of 1.15 m were recorded as 13 particles/m^3, 19 particles/m^3, 24 particles/m^3, 26 particles/m^3, and 27 particles/m^3 for the respective cases (baseline case to case 4).

Acknowledgements

The authors acknowledge the Ministry of Education (MOE) through Fundamental Research Grant Scheme (FRGS/1/2020/TK0/UTM/02/42) that was provided for this study. This research was also supported by the Universiti Teknologi Malaysia, UTMER grant with reference no. 19J15.

References

1) N. Kamsah, H. M. Kamar, M. I. Alhamid and K. Y. Wong, Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 44 (1), 12-23 (2018).
2) G. R. Doyle and J. A. McCutcheon, Clinical procedures for safer patient care. (BC Open Textbook Project, 2015).
3) H. Han, M. Hatta and H. Rahman, Evergreen 6 (1), 44-51 (2019). doi.org/10.5109/2321005
4) R. A. Borchardt and D. Tzizik, Journal of the American Academy of Pas 31 (4), 52-54 (2018).
5) H. M. Kamar, N. Kamsah, K. Y. Wong, M. N. Musa and M. S. Deris, Jurnal Teknologi (Science & Engineering) 77 (30), 63-67 (2015).
6) S. Sadrizadeh, J. Pantelic, M. Sherman, J. Clark and O. Abouali, Journal of Infection and Public Health 11 (5), 631-635 (2018).
7) M. Sathish and C. Girinivasan, Global spine journal, 2192568220937286 (2021).
8) A. J. Malek, S. V. Stafford, H. T. Papaconstantinou and J. S. Thomas, Journal of Surgical Research 265, 64-70 (2021).
9) Z. Li, H. Li, P. Lv, X. Peng, C. Wu, J. Ren and P. Wang, Scientific Reports 11 (1), 7794 (2021).
10) S. S. Magill, W. Hellinger, J. Cohen, R. Kay, C. Bailey, B. Boland, D. Carey, J. de Guzman, K. Dominguez and J. Edwards, Infection Control & Hospital Epidemiology 33 (3), 283-291 (2012).
11) S. Stewart, C. Robertson, J. Pan, S. Kennedy, L. Haahr, S. Manoukian, H. Mason, K. Kavanagh, N. Graves, S. J. Dancer, B. Cook and J. Reilly, Journal of Hospital Infection 114, 23-31 (2021).
12) E. Y. Killien, R. L. N. Huijsmans, M. S. Vavilala, A. M. Schleyer, E. F. Robinson, R. G. Maine and F. P. Rivara, Journal of Surgical Research 264, 334-345 (2021).
13) D. R. Bhatta, S. Hosuru Subramanya, D. Hamal, R. Shrestha, E. Gauchan, S. Basnet, N. Nayak and S. Gokhale, Antimicrobial Resistance & Infection Control 10 (1), 26 (2021).
14) K. McAulay, A. N. Schuetz, K. Fauntleroy, L. Shen, Y.-M. Merveille, A. Deroncelay, N. Cole, D. W. Fitzgerald and O. Ocheretina, Journal of Global Antimicrobial Resistance 25, 60-65 (2021).
15) H. Tan, K. Y. Wong, B. B. Nyakuma, H. M. Kamar, W. T. Chong, S. L. Wong and H. S. Kang, Environ Sci Pollut Res Int 29 (5), 6710-6721 (2022).
16) D. J. Anderson and K. S. Kaye, Infectious disease clinics of North America 23 (1), 53-72 (2009).
17) J. Liu, H. Wang and W. Wen, Building and Environment 44 (11), 2284-2289 (2009).
18) S. Sadrizadeh and S. Holmberg, Journal of Infection and Public Health 7 (6), 508-516 (2014).
19) S. Sadrizadeh, S. Holmberg and A. Tammelin, Building and Environment 82, 517-525 (2014).
20) A. Traversari, C. Goedhart, E. Dusseldorp, A. Bode, F. Keuning, M. Pelk and M. C. Vos, Journal of Hospital Infection 85 (2), 125-133 (2013).
21) S. H. Ho, L. Rosario and M. M. Rahman, Applied Thermal Engineering 29 (10), 2080-2092 (2009).

22) O. M. Ibrahim and S. Yoshida, Evergreen 5 (3), 12-21 (2018). doi.org/10.5109/1957496
23) C. Li and K. Ito, Evergreen 1 (1), 40-47 (2014). doi.org/10.5109/1440976
24) H. M. Kamar, K. Y. Wong and N. Kamsah, Journal of Building Performance Simulation 13 (6), 684-706 (2020).
25) W. Wang, Y. Cao and T. Okaze, Building and Environment 195, 107717 (2021).
26) K. Y. Wong, M. K. Haslinda, K. Nazri and S. N. Alia, Evergreen 6 (1), 52-58 (2019). doi.org/10.5109/2321008
27) N. Olleh, N. A. Husain, H. M. Kamar, N. B. Kamsah and M. I. Alhamid, Evergreen 8 (1), 163-169 (2021). doi.org/10.5109/4372273
28) K. Wong, H. Kamar and N. Kamsah, International Journal of Automotive and Mechanical Engineering 16 (4), 7447-7463 (2019).
29) L. Kwaśniewski, Bulletin of the Polish Academy of Sciences: Technical Sciences 61 (1), 123-128 (2013).
30) S. Sadrizadeh, S. Holmberg and P. V. Nielsen, Science and Technology for the Built Environment 22 (3), 337-345 (2016).
31) X. Ho, W. S. Ho, K. Y. Wong, M. H. Hassim, H. Hashim, Z. Ab Muis, N. A. Yunus and G. H. T. Ling, CHEMICAL ENGINEERING 83 (2021).
32) K. Q. Lee, A. Aminudin and M. Pauziah, Advanced Materials Research 664, 878-883 (2013).
33) A. A. Traversari, C. A. Goedhart, E. Dusseldorp, A. Bode, F. Keuning, M. S. Pelk and M. C. Vos, J Hosp Infect 85 (2), 125-133 (2013).