MEDICAL STAFF’S MOVEMENT EFFECTS ON PARTICLE COUNTS IN A SURGICAL ZONE

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DEDICATION

This thesis is dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

Movement by humans in healthcare facilities is unpreventable, especially among medical staff performing surgical procedures in an operating room. The movements can generate a secondary airflow that interrupts air supplies from ceiling-mounted diffuser, that serves to remove airborne particles from surgical zone. Consequently, the movement of particles in the surgical zone is affected, and the tendency of particles to fall onto patient's wound is increased. This situation could elevate the chances of a patient contracting surgical site infections and could increase the risk of death. The present study aims to examine the effects of medical staff's turning movements on the number of particles falling onto a patient. A simplified computational fluid dynamics (CFD) model of the operating room was developed and validated based on published data. A Re-Normalisation Group k-ε turbulence model based on the Reynolds-Averaged Navier-Stokes equations was used to simulate airflow, while a discrete phase model was used to simulate movement of airborne particles. The medical staff's turning movements were controlled by integrating a user-defined function code and using a dynamic mesh method. Results show that medical staff's turning movements have a significant influence on the airflow velocity distribution and the airborne particle concentration around the patient. Replacing the turning bent-forearm medical staff with the stationary bent-forearm medical staff reduced the number of particles that settled on a patient by 60.9 %, while substituting the turning straight-forearm medical staff with the stationary straight-forearm medical staff lowered the settlement of particles by 37.5 %. Results also indicated that employing single large diffuser (SLD) ventilation in the operating room, it reduced the number of particles that move into the surgical zone under the influence of medical staff's turning movements. The particles that settled on the patient were reduced by 41 % and 39 % when using the SLD 1 and SLD 2 ventilation, respectively. Present work confirmed that integrating the medical staff's turning movement in the vicinity of surgical zone is important as it reflects a more realistic condition. Considering only the stationary medical staff in simulation could underestimate the number of particles move into the surgical site and settling on a patient.

ABSTRAK

Pergerakan kakitangan perubatan di dalam bilik bedah tidak dapat dielakkan, terutamanya semasa mereka sedang melakukan prosedur pembedahan. Pergerakan mereka boleh menyebabkan gangguan kepada aliran udara yang dibekalkan oleh penyebar udara di siling, yang berfungsi untuk mengeluarkan zarah di udara dari ruang bedah. Akibatnya, pergerakan zarah dalam ruang pembedahan terjejas dan kecenderungan untuk ia jatuh ke atas luka pesakit meningkat. Keadaan ini boleh meningkatkan peluang pesakit mengalami jangkitan yang disebabkan oleh pembedahan, dan meningkatkan risiko kematian. Kajian ini bertujuan untuk menganalisa kesan pergerakan manusia terhadap bilangan zarah yang jatuh ke atas pesakit. Model dinamik bendalir berkomputer *(CFD)* bilik bedah dibangunkan dan disahkan menggunakan data hasil kerja yang telah diterbitkan. Model *Re-Normalisation Group* k-ε berdasarkan persamaan *Navier-Stokes Reynolds-Averaged* telah digunakan untuk mensimulasi aliran udara, manakala model fasa penuh digunakan untuk mensimulasi pergerakan zarah. Pergerakan manusia dikawal oleh kod fungsi takrifan pengguna dan kaedah jaringan dinamik. Hasil kajian menunjukkan bahawa pergerakan manusia mempunyai pengaruh yang ketara ke atas halaju aliran udara dan bilangan zarah di sekitar pesakit. Dengan menggantikan lengan bengkok staf dengan lengan bengkok pegun, bilangan zarah yang jatuh ke atas pesakit berkurang sebanyak 60.9%, manakala menggantikan lengan lurus staf dengan lengan lurus pegun, bilangan zarah dapat dikurangkan sebanyak 37.5%. Hasil kajian juga menunjukkan bahawa dengan menggunakan pengudaraan penyebar besar tunggal *(SLD)*, ia mampu mengurangkan bilangan zarah dalam zon bedah. Bilangan zarah yang jatuh ke atas pesakit dapat dikurangkan masing-masing sebanyak 41% dan 39% apabila menggunakan pengudaraan *SLD 1* dan *SLD 2*. Kajian ini mengesahkan bahawa penyepaduan pergerakan kakitangan perubatan di sekitar zon pembedahan adalah penting kerana ia mencerminkan keadaan yang lebih realistik. Mengandaikan bahawa semua kakitangan perubatan dengan keadaan pegun untuk simulasi dapat mengurangkan anggaran bilangan zarah bergerak ke tapak pembedahan dan menetap pada pesakit.

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LIST OF ABBREVIATIONS

AC	-	Air Curtain
AIA	-	American Institute of Architects
ASHE	-	The America Society for Healthcare Engineering
ASHRAE	-	American Society of Heating, Refrigerating, and Air Conditioning Engineers
BCP	-	Bacteria-Carrying Particle
CAD	-	Computer-Aided Design
CFD	-	Computational Fluid Dynamic
CoNS	-	Coagulate-Negative Staphylococcus Aureus
DES	-	Detached Eddy Simulation
DPM	-	Discrete Phase Model
FEM	-	Finite Element Method
FVM	-	Finite Volume Method
GCI	-	Grid Convergence Index
GIT	-	Grid Independent Test
HAI	-	Hospital Associated Infection
HEPA	-	High-Efficiency Particulate Air
IAQ	-	Indoor Air Quality
ICU	-	Intensive Care Unit
ISO	-	International Organisation for Standardisation
LES	-	Large Eddy Simulation
MDA	-	Multi-Diffuser Array
MRSA	-	Methicillin-Resistant Staphylococcus Aureus
MUSCL	-	Monotonic Upstream-Centred Scheme for Conservative Law
OR	-	Operating Room
PISO	-	Pressure Implicit with Spitting Operators
PIV	-	Particle Image Velocimetry
PM	-	Particulate Matter
QUICK	-	Quadratic Upstream Interpolation for Convective Kinematics
RANS	-	Reynolds-Averaged Navier Stokes

RH	-	Relative Humidity
RNG	-	Re-Normalisation Group
RSM	-	Reynolds Stress Model
SARS	-	Severe Acute Respiratory Syndrome
SIMPLE	-	Semi-Implicit Method for Pressure Linked Equations
SIMPLEC	-	Semi-Implicit Method for Pressure Linked Equations-Consistent
SIMPLER	-	Semi-Implicit Method for Pressure Linked Equations-Revised
SLD	-	Single Large Diffuser
SSI	-	Surgical Site Infection
SST	-	Shear-Stress Transport
UDF	-	User-Defined Function

LIST OF SYMBOLS

A	-	Area
$\vec{A}$	-	Face area vector
C	-	Particle concentration
C_{dim}	-	Dimensionless particle concentration
C_{ref}	-	Reference particle concentration
$C_{1\varepsilon}$, $C_{2\varepsilon}$	-	Constants in the modelled ε equation
D	-	Diameter
F_a	-	Additional force
F_D	-	Drag force
F_s	-	Safety factor
G_k	-	Generation of turbulence kinetic energy due to mean velocity gradients
G_b	-	Generation of turbulence kinetic energy due to buoyancy
H	-	Height
L	-	Length
N, n	-	Number of samplings
Pa	-	Pascal
Re	-	Reynolds number
R_ε	-	Additional term in ε equation
S_c	-	Source term
S_k, S_ε	-	User-defined source term
T	-	Time
V	-	Volume
X_i	-	i_{th} measurement of the parameter X
$\dot{X}$	-	Average value of the measured parameter
W	-	Watt
W	-	Width
Y_M	-	Contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate
g	-	Gravity

k	-	Kinetic energy
p	-	Order of convergence
r	-	Refinement factor
t	-	Time
u	-	Air velocity
u_p	-	Particle velocity
u_f	-	Final air velocity
u_i	-	Initial air velocity
$\bar{u}_i$	-	Averaged air velocity components in the three directions
$\vec{u}$	-	Airflow velocity vector
$\overrightarrow{u_g}$	-	Mesh velocity of the moving mesh
v	-	Kinematic viscosity
x_i	-	Coordinate
y	-	Distance normal to the wall
y^+	-	Dimensionless wall distance
ε	-	Turbulent dissipation
ε	-	Relative difference
ρ	-	Density of air
ρ_p	-	Density of particle
μ	-	Micro
μ_{eff}	-	Effective viscosity
μ_τ	-	Friction velocity
Γ	-	Effective particle diffusivity
σ	-	Standard deviation
α_k	-	Prandtl number for kinetic energy
α_ε	-	Prandtl number for turbulent dissipation
τ_w	-	Wall shear stress
ω	-	Specific turbulent dissipation
$\emptyset$	-	General scalar

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CHAPTER 1

INTRODUCTION

1.1 Problem Background

An operating room (OR), also known as an operating theatre, is a healthcare facility that enables surgeons to carry out surgical operations. The majority of ORs worldwide employ cleanroom technology to provide a highly controlled and clean environment for both the patients and the hospital's personnel. It is necessary to maintain a contaminant-free environment for the patient during surgical procedures. Recent studies concluded that 98 % of surgical site infections (SSI) were due to the settlement of airborne particles on the patients' wounds (Chauveaux, 2015; Talon *et al.*, 2006). A study conducted by Karlatti and Havannavar (2016) found that post-operational SSI rates were increased when the surgery was performed in unclean surroundings. It has been estimated that nearly 3 % to 5 % of patients who underwent surgery in clean environments developed SSIs (Singh, Singla and Chaudhary, 2014), whereas surgical procedures performed in ultra clean environments were associated with an SSI incidence rate as low as 1 % (Olsen *et al.*, 2016).

SSI is defined as any infection that follows an operative procedure which occurs at or near the surgical incision site within 30 days of the procedure (Karlatti *et al.*, 2016; Mangram *et al.*, 1999). SSIs are ranked third amongst the most common hospital associated infections (HAI). They make up 13- 17 % (Anderson *et al.*, 2014; Birgand *et al.*, 2015) and 10- 40 % (Singh *et al.*, 2014) of the total HAI cases reported in Europe and the USA, respectively. Singh *et al.* (2014) found that in over 27 million operations performed annually in the USA, SSIs were reported in approximately 300,000 cases, of which 8,000 ended in mortality (Singh *et al.*, 2014). SSIs are associated with an increased risk of death, additional treatment costs and prolonged hospital stays. The rate of post-operative morbidity has increased from 65 % to 80 % due to the increment in the number of SSI cases (Chow and Wang, 2012) and has caused a rise of hospitalisation costs by 3,000 USD to 29,000 USD per case depending on the type of surgical procedure performed (Magill *et al.*, 2012). One valid example is a case study presented by Chow *et al.* (2012), where the medical care expenses for a patient with a prosthetic joint SSI reached 100,000 USD. On average, the infected patient will need to extend his/her hospital stay by about 7 to 10 days for additional treatment (Ata *et al.*, 2010; Magill *et al.*, 2012).

To promote a highly conducive environment in the OR, aseptic techniques such as room cleaning, disinfection and sterilisation are conducted upon the completion of each surgical procedure. Also, the ventilation system inside the OR is specially designed to produce a particle- and sediment-free environment. The principal use of this system is to filter unwanted residues from the outdoors and prevent them from entering the OR and to remove the existing particles in the adjacent area. Standard (2008) proposed that the air supply diffuser should extend a minimum of 305 mm beyond the footprint of the operating table on each side. The zone bounded by the footprint area is assumed to be the surgical zone, as surgical procedures are performed within the region. The direction of the airflow and the rate of air change in the OR are the main factors in determining the amount of airborne particle settlement (Memarzadeh, 2003). Air change rate is defined as the measure of the volume of air supply added to a confined space in an hour. Under adequate air exchange conditions, the contaminated air could effectively be replaced by fresh clean air. Standard (2008) recommends that practitioners employ a unidirectional airflow ventilation in the OR. The supply air diffuser is located on the ceiling, while the air is exhausted to the adjacent area through exhaust grilles near the floor. This unidirectional airflow is capable of reducing the number of airborne bacteria and the risk of surface contamination at the surgical sites (Sadrizadeh and Holmberg, 2015). A proper air change rate could further reduce the number of particles inside the OR. Many studies have been carried out to ascertain the appropriate air change rate. The proposed air change rate is in the range of 8/h to 20/h (Li, Zou and Wang, 2014; Memarzadeh and Xu, 2012; Pereira *et al.*, 2013). For a constant particle generation rate inside an OR, a higher air change rate could improve the removal rates of the airborne particles.

The setting of the air diffusers also affects the airborne particle concentration in an OR. The proposed air delivery layouts vary from ceiling-mounted to side wall-mounted, diagonal and additional mobile air supply units (Pereira and Tribess, 2004; Sadrizadeh, Holmberg and Nielsen, 2016b; Ufat *et al.*, 2017; Woloszyn, Virgone and Mélen, 2004). Each of these strategies has its advantages and disadvantages in terms of particle removal efficiency. The ceiling-mounted type, however, has been found to be less sensitive towards the placement of obstacles. The remaining layouts rely heavily on the positioning of medical personnel, the equipment table, medical equipment and other furniture. During surgical procedures, the movements of the medical staff are unpredictable, hence, the ceiling-mounted air supply is the most favourable strategy to be employed in the OR. Recently, Wagner and Schreiber (2014) tested several layouts that fulfilled the criteria of being ceiling-mounted air diffusers as stated in Standard (2008), namely, multi-diffusers, a single large diffuser, and a combination of diffusers and air curtains. A single large diffuser was found to be effective in preventing airborne contaminants from settling in the surgical zone (Wagner *et al.*, 2014).

Commonly, nine medical staff will be present in the OR for complex surgery, namely, a surgeon, three assistant surgeons, a scrub nurse, a circulating nurse, an anaesthetist, an assistant anaesthetist, and an X-ray technician (Oliveira and Gama, 2015). Minor surgery, however, involves only five medical staff: a surgeon, an assistant surgeon, a circulating nurse, an anaesthetist, and an assistant anaesthetist (Oliveira *et al.*, 2015). The number of staff present in the OR, however, varies on a case-by-case basis. Recently, Wang and Chow (2015) reported that in China, a total of seven staff participate in a surgical procedure, whereas, in Italy, only five staff are involved in an operation (Romano *et al.*, 2015). Surprisingly, Sweden has the highest number of staff engaged in a surgical procedure, which is ten staff (Sadrizadeh, Holmberg and Tammelin, 2014b). During a surgical procedure, a surgeon performs the actual incisions and makes the critical decisions. The assistant surgeon assists the surgeon by providing surgical tools, clamping vessels during surgery, and stitching up the incisions. Both the anaesthetist and assistant anaesthetist are in charge of safely administering anaesthesia to patients before surgery, monitoring them during surgery, and ensuring that they safely come out of anaesthesia after the surgery. The responsibility of the circulating nurse is to deliver additional supplies that may be needed during surgery and to document the surgery. On the other hand, the role of the scrub nurse is to sterilise the instruments before and after the surgery, to keep the surgical field organised during surgery, and to provide the surgeon with the necessary instruments.

1.2 Problem Statement

An ideal OR should have excellent healthcare facilities to provide patients with safe surgical treatment. However, having equipment alone is not sufficient if the hygiene of the OR is disregarded. Managing a clean environment is essential for preventing SSI due to the settlement of suspended particles on a patient's wound. The primary source of airborne particles is from medical personnel and this could become more critical if they are making significant movements near the patient (Buchanan and Dunn-Rankin, 1998; Chauveaux, 2015; Talon *et al.*, 2006). The adverse effect of such movement is that it will expedite the rate of release of particles from the staff and interfere with the oncoming unidirectional airflow of the air supply diffuser to push the particles away from the surgical zone (Shih, Chiu and Wang, 2007). Consequently, the effectiveness of the clean air to wash away the particles which have been shed, could be reduced and the possibility of particles settling on a patient wound will be increased. Before further addressing this problem, a comprehensive evaluation should be carried out to examine the effects of movement of medical personnel on particle concentration in the vicinity of the surgical zone. However, the personnel should not be treated as static dummies that just release particles. Any analysis should include their movement behaviour. Indeed, disregarding the effect of human movement was identified as the main shortfall in assessing the effectiveness of ventilation in a building (Khazaii, 2016). To study the aspects of a moving object, one should consider dynamic and transient features in the analysis to achieve realistic outcomes (Romano *et al.*, 2015). Therefore, the goal of this study is to undertake particle counts to assess the number of particles that settle on a patient, taking into account the influence of medical staff's movements, by using a numerical approach. A 3-D computational model of an OR was constructed using computer-aided design (CAD) software. Computational fluid dynamic (CFD) software was used to simulate particle transport under transient conditions. The effects of a turning movement by medical staff was included in the analysis. A validation of the CFD model based on the published data was performed, and a user-defined function (UDF) written in C language software was incorporated into the analysis to create the turning movement of the medical personnel. Finally, the effectiveness of incorporating a single large diffuser (SLD) in reducing the particle concentration at the surgical zone was examined.

1.3 Objectives of the Research

The goal of this study is to examine the particles that settle on a patient due to the movement of medical staff, by using a numerical approach. Based on this research goal, three research objectives have been identified as follows: -

1. to develop the validated CFD models of a patient ward and an environmental chamber.
2. to predict the number of particles settling on a patient due to medical staff's movement and posture.
3. to assess the effectiveness of a single large diffuser (SLD) in reducing the particle concentration in the surgical zone and settlement on patients considering the effect of medical staff's turning movement.

1.4 Scope of the Research

This study limits its scope to the following points: -

1. Commercial CFD software was used to simulate the particle transportation and airflow inside the computational domain.
2. The baseline model of the OR was developed in accordance with the actual dimensions of an International Organisation of Standardisation (ISO) Class 7 OR, with dimensions of 6 m (length) × 5.5 m (width) × 3 m (height).
3. The movement of medical staff was restricted to turning movements with an angular velocity of 1.57 rad/s.
4. A Lagrangian particle tracking model was used to simulate particle trajectories.

5. The airflow analysis was performed under two conditions: a steady and a transient condition.
6. The medical staff were considered under a stationary and a dynamic condition.
7. The gravitational force is 9.81 m/s^2.
8. The particles are released from the surface of staff at a rate of 600 particles/min per person.
9. The OR is in positive pressurization, with no intrusion of airborne particles from the door gap or adjacent rooms.

1.5 Significance of the Research

A comprehensive evaluation to examine the significant effects of medical personnel's movements on particle settlement in the vicinity of the surgical zone is essential for addressing the problem of SSIs. A numerical method is crucial to predict the behaviour of the suspended particles on human movement. However, to produce realistic and reasonable results, the model simulation should be performed under dynamic conditions. Most of the recent studies have disregarded the dynamic behaviour of the model. Although the latter approach could save computational time, it is incapable of giving reasonable outputs. Furthermore, the dynamic analysis is capable of modelling the realistic behaviour of a moving person. So far, no studies have reported the effect of particles shed by moving humans in the OR. Understanding the relationships between moving medical staff, airflow patterns, and the number of particles, will provide knowledge that will be useful in minimising the settlement of suspended particles on patients' wounds. This may potentially cause a reduction in the number of SSIs, thus resulting in a drop in the number of deaths. The proposed approach could be used as an option for researchers who are undertaking related studies. The research findings will be beneficial to investigators and engineers who are involved in cleanroom design and construction.

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Appendix A PC Setup for Compiling the UDF Code

Window	7 Home Premium- 64 bit	10 Home- 64 bit
Simulation software	ANSYS Fluent 14.0	ANSYS Fluent 14.0
Additional software	1) Microsoft Visual C++ 2008 Express Edition 2) Microsoft .NET Framework SDK V2.0	1) Microsoft Visual Studio 2013 Express 2) Windows Software Development Kit 8.1 3) Microsoft .NET Framework 4.5.1
Environmental variables setup	Adding the ";C:\Program Files (x86)\Microsoft Visual Studio 8.0\Common7\Tools;C:\Program Files (x86)\Microsoft Visual Studio 8.0\VC\bin;C\Program Files\ANSYS Inc\v140\fluent\ntbin\win64" at the "path" variable	Adding the ";C:\Program Files (x86)\Microsoft Visual Studio 14.0\VC\bin\x86_amd64" at the "path" variable
Initiating simulation software	Using the SDK command prompt	Using visual studio Cross Tools Command Prompt

LIST OF PUBLICATIONS

Indexed Journal

1. Wong, K.Y., Kamar, H.M., Kamsah, N. Effects of surgical staff turning motion on airflow distribution inside a hospital operating room. *EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy*. (Accepted for publication)

2. Wong, K.Y., Kamar, H.M., Kamsah, N., Zawawi, F.M., Tan, H., Musa, M.N., Deris, M.S. (2018). Correlation between particulate matter and microbial counts in hospital operating rooms. *Advances in Environmental Biology*. 12(10), 1-4.

3. Kamsah, N., Kamar, H.M., Alhamid M.I., Wong, K.Y. (2018). Impacts of temperature on airborne particles in a hospital operating room. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences.* 44 (1), 12-23.

4. Wong, K.Y., Kamar, H.M., Kamsah, N., Zawawi, F.M. (2017). Effects of staff movement and air change rate on the airflow fields in a hospital's operating room. *International Journal of Control Theory and Applications*. 10 (03), 265-275.

5. Kamar, H.M., Kamsah, N., Wong, K.Y., Musa, M.N., Deris, M.S. (2015). Field measurement of airborne particulate matters concentration in a hospital's operating room. *Jurnal Teknologi*. 77 (30), 63-37.

6. Tan, H. Wong, K.Y., Kamar, H.M., Kamsah, N., Deris, M.S. (2017). A systematic airborne particle measurement in a GMP grade c hospital's preparation room. *International Journal of Control Theory and Applications*. 10 (3), 257-263.

Non-Indexed Journal

1. Wong, K.Y., Kamar, H.M., Kamsah, N., Zawawi, F.M., Deris, M.S. (2017). Comparison of turbulence models in solving the airflow in a unidirectional airflow operating room. *International Journal of Advanced Research in Engineering & Technology*. 1 (3), 7-11.

2. Wong, K.Y., Kamar, H.M., Kamsah, N., Tan, H. Deris, M.S. (2016). Comparison of cleanroom performance in hospital culture and vascular interventional radiology laboratories. *International Journal of Advances in Science, Engineering and Technology*. 4 (4), 71-75.

3. Wong, K.Y., Kamar, H.M., Kamsah, N., Tan, H. Deris, M.S. (2017). Real-time measurements of relative humidity and temperature in hospital operating room. *International Journal of Mechanical and Production Engineering*. 5 (10), 92-95.

4. Wong, K.Y., Kamar, H.M., Kamsah, N., Zawawi, F.M., Deris, M.S. (2017). Effect of air change rate on airborne particles concentration in hospital operating rooms. *International Journal of Advanced Research in Engineering & Technology*. 1 (3), 1-6.

5. Wong, K.Y., Kamar, H.M., Kamsah, N., Zawawi, F.M., Deris, M.S. (2017). Cleanroom performance testing in hospital's vascular interventional radiology laboratory. *International Journal of Mechanical and Production Engineering.* 5 (10), 86-91.

Indexed Conference Proceedings

1. Kamsah, N., Kamar, H.M., Kamaruddin, N.F.H., Wong, K.Y., Zawawi, F.M. (2017). Effect of surgical lamp and staff surface temperatures on particles distribution in a hospital operating room. *9th International Meeting on Advances in Thermofluids*. 23.

Non-Indexed Conference Proceedings

1. Wong, K.Y., Kamar, H.M., Kamsah, N. (2018). Simulation of airflow and airborne particles movement inside a hospital operating room. *Proceedings of the 7th IGCESH 2018 International Graduate Conference on Engineering, Science and Humanities.*

2. Wong, K.Y., Kamar, H.M., Kamsah, N. (2018). Efficiency of three distinct types of mesh for indoor airflow simulation. *Proceedings of IAARHIES International Conference. 45*

3. Wong, K.Y., Kamar, H.M., Kamsah, N., Zawawi, F.M., Musa, M.N., Deris, M.S. (2016). A systematic assessment of cleanroom performance in hospital's operating room. *Proceedings of 9th & 10th IAARHIES International Conferences*. 6-11.
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5. Wong, K.Y., Kamar, H.M., Kamsah, N., Deris, M.S., Tan, H. (2016). Comparison of cleanroom performance in hospital culture and vascular interventional radiology laboratories. *Proceedings of 18th Research World International Conference*. 27-31.