Research Article

THE CENTER FOR HEALTH DESIGN®

Health Environments Research & Design Journal
1-9
© The Author(s) 2019
Article reuse guidelines:
sagepub.com/journals-permissions
DOI: 10.1177/1937586719854218
journals.sagepub.com/home/her

SAGE

Analyzing ICU Patient Room Environmental Quality Through Unoccupied, Normal, and Emergency Procedure Modes: An EQI Evaluation

Jennifer A. Wagner, PhD, CIC[1], Damon G. Greeley, PE, CEM, HFDP, CBCP, EDAC, CHFM[2], Thomas C. Gormley, PhD, LEED, AP, CHC[3], and Troy A. Markel, MD[4]

Abstract

Background: There is increasing need to perform invasive surgical procedures in intensive care units (ICUs). Traditional ICUs differ from operating rooms (ORs) in several ways including air changes per hour (ACH) and pressurization. Increased ACH and positive pressurization of ORs intend to provide more aseptic environments for surgery. Development of procedure ready ICUs that transition through unoccupied, occupied, and procedure modes is one solution to improve environmental quality when performing surgery in ICUs. This study assessed the efficacy of two airflow control systems, variable air volume (VAV) and Venturi control, in preventing contaminants from entering ICU from adjacent corridors. **Study Design:** Controlled contaminants, sulfur hexafluoride (SF6) and baker's yeast (CFU/m^3), were released in the corridor adjacent to the ICU. SF6 and CFU/m^3 were detected inside the ICU at the patient bed during a dynamic simulation of code blue event. VAV and Venturi were compared as they cycled the room through unoccupied, occupied, and procedure modes. **Results:** VAV and Venturi showed significantly fewer CFU/m^3 at the patient bed than corridor point of release ($p < .05$). Although not significant, Venturi cultured 14% fewer CFU/m^3 than VAV at the patient bed. There was less SF6 detected at the patient bed with VAV and Venturi ($p < .05$). There was less SF6 detected at the patient bed with Venturi compared to VAV ($p < .05$). Venturi transitioned between modes faster than VAV ($p < .05$). **Conclusion:** Using efficient mode transitioning systems in ICUs may be effective in creating a more aseptic environment that mimics that of the OR.

[1] OnSite-LLC, Prism Environmental Health and Safety, Inc, Discovery Bay, CA, USA
[2] OnSite-LLC, Global Health Systems, Inc, Fort Mill, IN, USA
[3] Music City Consulting, LLC, Nashville, TN, USA
[4] Geist Medical Consulting, LLC, Indianapolis, IN, USA

Corresponding Author:
Jennifer A. Wagner, PhD, CIC, OnSite-LLC, Prism Environmental Health and Safety, Inc, PO Box 1702, Discovery Bay, CA 94505, USA.
Emails: jwagner@onsite-llc.com; jwagner@prismehs.com

Keywords
procedure ready ICU room, variable air volume (VAV), Venturi valve, ACH, room pressure, American Society of Heating, Refrigeration and Air Conditioning Engineers, heating, ventilation, and air conditioning, environmental quality indicators (EQI)

Background

Efficient use of the intensive care unit (ICU) is a priority for modern healthcare (Management, 1999). ICU admissions, triage, and discharge guidelines exist to streamline the appropriate use of the ICU in an effort to maximize patient survival while using resources effectively and efficiently. Patients can be admitted to the ICU from a variety of different locations including the emergency department, the operating room (OR), or from another hospital. The determination of admission to the ICU is dependent on many factors including the potential requirement for additional procedures (Nates et al., 2016).

The development of a flexible critical care space that can provide the sterility and safety of an OR without the need to transport patients to other areas is essential for the changing landscape of healthcare. Common bedside procedures may need to be performed in the ICU when either the patient is too sick or injured to be safely moved to the OR, if the timeliness of critical care is of essence such as in cardiac arrest or if the OR is unavailable due to staffing or logistical reasons. It is estimated that moving a critically ill patient within the hospital increases the risk of an adverse event occurring by 30–45% (Dennis et al., 2013); Beckmann et al., 2004; Winter, 2010; Parmentier-Decrucq, 2013). Additionally, in some cases, it is more cost-effective to perform certain procedures in the ICU (Mirski et al., 2012); Pandian et al., 2012). According to Dennis et al (2013), similar outcomes and significant cost reductions have been noted when percutaneous tracheostomy, endoscopic gastrotomy, inferior vena cava filter, laparotomy and orthopedic damage control were performed in the ICU instead of the OR (Dennis et al., 2013).

The development of a flexible critical care space that can provide the sterility and safety of an OR without the need to transport patients to other areas is essential for the changing landscape of healthcare.

A typical ICU room differs in its environment from the OR in size and functionality. ICU patient rooms can be less than one third the size of an OR and typically contain a toilet room which can affect pressurization and result in potential aerosolization of contaminants. ICU rooms also often lack the stringent, protective air delivery over the procedure site, a higher air exchange rate, and the necessary positive pressure to prevent contaminants in the corridor from entering the room. The American Society for Heating, Refrigeration and Air conditioning Engineers guidelines for design, construction, and engineering of the ICU recommend MERV 14 filters, 6 air changes per hour (ACH) with 2 outside air, no defined pressurization relationship with the corridor, 30–60% relative humidity (RH), and a temperature of 70–75 °F. In comparison, for an OR, MERV 14 filters, 20 ACH with 4 outside air, positive pressurization of 0.01" to the corridor, 20–60% RH, and a temperature of 68–75 °F are recommended (The American Society of Heating, 2013).

ICU rooms also often lack the stringent, protective air delivery over the procedure site, a higher air exchange rate, and the necessary positive pressure to prevent contaminants in the corridor from entering the room.

Designing and engineering an ICU that is capable of seamlessly transitioning from unoccupied to occupied to procedure and back to

occupied modes will increase the flexibility of the patient space making it more suitable for the already indicated procedures, as well as additional procedures that are currently contraindicated for the ICU room. The impact of this engineering control may improve outcomes by reducing intrahospital patient transport and operational cost while improving the environmental contamination control by minimizing the contamination that can enter or remain in the room at increased ACH. A solution to designing a "procedure ready" ICU includes the ability of the heating, ventilation, and air conditioning system to change the ACH and pressurization of the ICU. By providing a relay circuit through the Code Blue Alert system, or a less-critical procedure mode, that would signal the building automation controls to change the ACH and pressure automatically, taking the ICU room to 15 ACH with a positive pressure relationship to the corridor. After the Code Blue Alert was canceled, a return to normal ventilation mode at 6 ACH with neutral pressurization could be achieved.

Designing and engineering an ICU that is capable of seamlessly transitioning from unoccupied to occupied to procedure and back to occupied modes will increase the flexibility of the patient space making it more suitable for the already indicated procedures, as well as additional procedures that are currently contraindicated for the ICU room.

A solution to designing a "procedure ready" ICU includes the ability of the heating, ventilation, and air conditioning system to change the ACH and pressurization of the ICU. By providing a relay circuit through the Code Blue Alert system, or a less-critical procedure mode, that would signal the building automation controls to change the ACH and pressure automatically, taking the ICU room to 15 ACH with a positive pressure relationship to the corridor

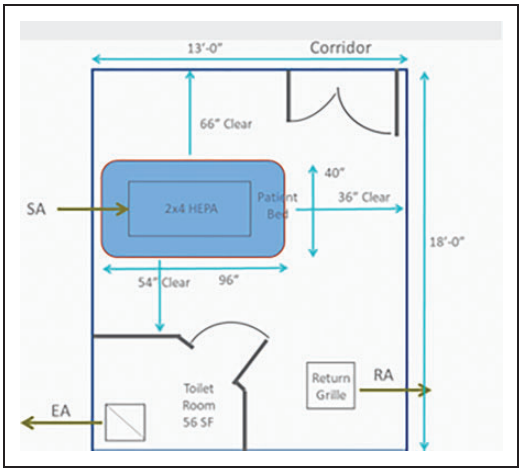

Figure 1. Design and layout of the mock ICU room.

This study assessed environmental quality indicators (EQI) and compared two airflow control systems (a variable air volume [VAV] air terminal and a Venturi type control air valve) in a dynamic procedural environment. We hypothesized that (1) using an airflow control system to cycle through ACH and pressure settings would dramatically decrease the amount of contaminant in the ICU room compared to the adjacent corridor and (2) the use of a Venturi valve would be equivalent to the use of a VAV in its ability to prevent corridor contaminants from entering the ICU when it was cycling to procedure mode.

Materials and Method

ICU Room Specifications

The ICU room was designed, engineered, and constructed in a Phoenix Controls manufacturer facility in Acton, MA. The room was 230 ft^2, 13 ft long, 18 ft wide, and 8 ft tall and was constructed as per the Facilities Guidelines Institute. The toilet room was 56 ft^2, there was a single 2 × 4 air supply diffuser with integral high efficiency particulate air diffuser over the bed and a single ceiling mounted return grille opposite the toilet room door. The room was adjacent to a mock corridor with double doors that opened into the room (Figure 1). The corridor was 13 ft long, 4 ft wide,

ICU Room Research Test Script FINAL (updated-092117)							
Team Member	Set-up Notes: 1. Don all PPE	0-3 min	3-6 min	6-9 min	9-12 min	12-15 min	15-18 min
Control Technicians	Set beginning airflow condition: 1. Test #1 Phoenix min to normal, normal to procedure	Begin at unoccupied mode		Transition to normal mode, waiting on samplers			Transition to procedure mode, waiting on samplers
Dr. Taylor (attending physician)		Hold in hallway	Hold in hallway	Enter room after samplers are loaded	Bring new plates, collected used plates	Bring new plates, collected used plates	Hold door open for 20 seconds
Dr. Wagner (med emergency response staff)	Prepare Baker's Yeast for release	Release controlled contaminant, Start stop samplers/change	Release controlled contaminant, Start stop samplers/change	Release controlled contaminant, Start stop samplers/change	Release controlled contaminant, Start stop samplers/change	Release controlled contaminant, Start stop samplers/change	Release controlled contaminant, Start stop samplers/change
Damon (visitor)	Confirm and record airflow & pressure Record temp & RH inside room	recording SF6, RH, temp, starting/stopping SAS samplers and	recording SF6, RH, temp, starting/stopping SAS samplers and	recording SF6, RH, temp, starting/stopping SAS samplers and	recording SF6, RH, temp, starting/stopping SAS samplers and	recording SF6, RH, temp, starting/stopping SAS samplers and	recording SF6, RH, temp, starting/stopping SAS samplers and
John (med staff)	Prepare SF6 for release in hallway	Control SF6 release in hallway	Control SF6 release in hallway	Control SF6 release in hallway	Control SF6 release in hallway	Control SF6 release in hallway	Control SF6 release in hallway

Figure 2. Sample testing script.

and 8 ft tall and was constructed with 6 mil polyethylene sheeting.

Controlled Contaminants

Two controlled contaminants were released in the corridor to measure the effectiveness of the two airflow control systems in their ability to prevent entrainment of the contaminants into the ICU room.

Saccharomyces cerevisiae. The baker's yeast, *S. cerevisiae*, in dry form, was premeasured into sterile glass scintillation vials (0.05 g) and sealed with parafilm. Immediately prior to each test, 5 mL of sterile water was added to the vial to suspend the yeast. The water yeast suspension was then added to 2 L of water in the chamber of a cool steam humidifier. The humidifier was run on high for the duration of the testing procedure, starting at $T = 0$. The aerosolized yeast was captured using Bioscience Surface Air Samplers (SAS 180; Bioscience International, Rockville, MD) calibrated for 114.5 L of air collected over 3.5 min with Malt Extract Agar (Hardy Diagnostics, Santa Maria, CA) at the point of release in the hallway and inside the ICU room at the patient bed. Eighteen samples were collected inside the ICU in six replicates of three. Six samples were collected at the point of origin in the corridor adjacent to the humidifier. The samples were transported under chain of custody, and colonies were enumerated in a randomized manner and reported as colony forming units per cubic meter (CFU/m^3).

Sulfur hexafluoride (SF6). The traceable gas, SF6 was released and controlled to maintain an average level of concentration of approximately 70 parts per million in the corridor and detected inside the ICU room at the head of the patient bed using a Thermo Scientific Miran SapphlRe portable ambient analyzer.

Research Team (Mock Medical Staff)

The mock medical staff consisted of four multidisciplinary team members, each with a defined, scripted, and repeatable role. The code blue procedure was led by the team's medical doctor or researcher who acted as the "attending physician" and simulated bringing the patient into the room, calling the code blue, resuscitating the patient and recovery from the procedure. Two team members, simulating "medical staff," operated the controlled contaminant releases in the corridor while the simulated "visitor" collected the biological samples and recorded the tracer gas readings at the patient bed. An expert control technician for both VAV and Venturi was present outside the corridor to operate the ICU room transitions from unoccupied to occupied to procedure modes.

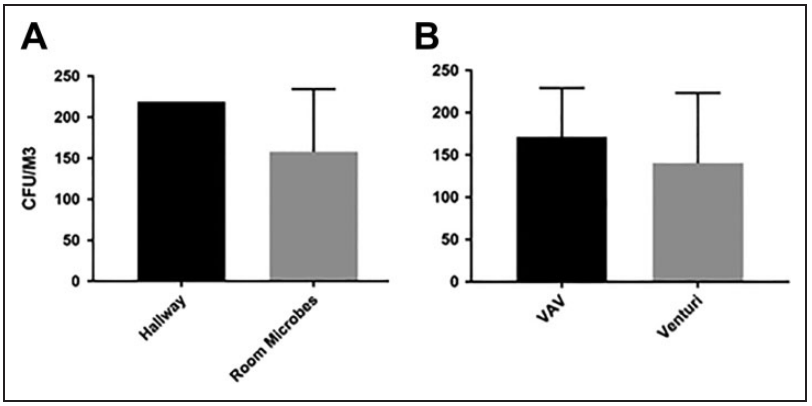

Figure 3. (A) Microbial controlled contaminant point of origin to ICU room comparison. Significant at $p < .05$. (B) Microbial in room controlled contaminant comparison of VAV to Venturi. Not significant at $p = .11$.

Table 1. Microbial Count Comparison by Time Interval.

Time (min)	Event	ACH	VAV CFU/ m^3	Venturi CFU/ m^3	Significance ($p < .05$)
0–8	Prior to first door opening	3 transition to 6	25.3–177	2–5	$p = .027$
9–24	After first door opening	Remain at 6	105.3–219	152–219	$p = .38$
25–36	After second door opening	6 transition to 15	134–219	149.3–216.5	$p = .42$
37–42	After third door opening	15 transition to 6	97–210.3	35–113	$p = .11$

Note. ACH = Air changes per hour; VAV = Variable air volume.

EQI Simulation

Assessment of the airborne contamination was adapted from the previously described EQI method (Gormley et al., 2017). The temperature and humidity were measured and recorded every minute for the duration of the testing. A precise and detailed scripted procedure cycled the ICU through the three stages of unoccupied, occupied, and procedure modes over a total of 50 min. For the yeast-controlled contaminant, each experiment was repeated 2 times with each airflow control system. Twelve sets of three data points were collected, for a total of 36 data points inside the room. In the corridor at the point of origin, a single sample at each of 12 data points was collected. For the tracer gas contaminant, each experiment was repeated 3 times with each airflow control system. The concentration of SF6 was recorded inside the ICU room and in the corridor each minute for the duration of the testing.

During each experiment, the door was opened a total of 3 times. The first door opening occurred at $T = 9$ min, included the opening of one of the double doors for 10 s, and was intended to simulate the entrance of the patient into the room and the transition from unoccupied to occupied mode. The second door opening occurred at $T = 24$ min, included opening both doors for 20 s, and was intended to simulate the code blue and influx of medical staff and equipment, and the transition from occupied to procedure mode. The third door opening occurred at $T = 39$ min, included opening one of the double doors for 20 s, and was intended to simulate the conclusion of the code blue, exit of medical staff and equipment, and the transition from procedure to occupied mode (Figure 2).

Airflow Control Systems

VAV and Venturi experiments were repeated in alternating pattern (i.e., VAV, Venturi, VAV,

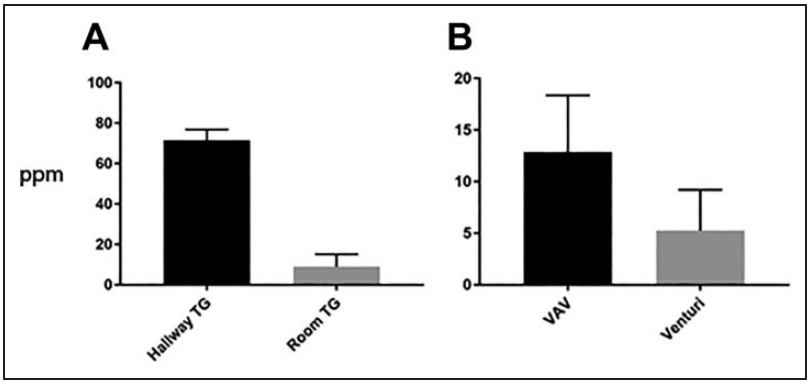

Figure 4. (A) SF6 controlled contaminant (tracer gas) point of origin to ICU room comparison. Significant at $p < .05$. (B) SF6 controlled contaminant in room comparison between VAV and Venturi. Significant at $p < .05$.

Venturi). During each experiment, the initial room airflow control system was set at 3 ACH at $T = 0$ (unoccupied), then changed to 6 ACH at $T = 9$ (occupied mode), elevated to 15 ACH at $T = 24$ (procedure mode), and final reduced back to 6 ACH at $T = 39$ (occupied mode). The transitions between air changes were achieved using a BACNet Configuration Tool (BCT), and the time to transition and stabilize between each ACH was measured with a stopwatch and recorded on the BCT screen.

Statistical Analysis

All statistical analyses were performed using GraphPad Prism 7 (GraphPad Software, La Jolla, CA). Data were assessed for normalcy by the Shapiro–Wilk and the Kolmogorov–Smirnov normality tests and reported as the mean with standard error of the mean (parametric) or median with interquartile range (nonparametric). Parametric data were compared with one-way analysis of variance and post hoc Tukey's multiple comparisons test. Nonparametric data were compared with the Kruskal–Wallis test followed by post hoc Mann-Whitney comparison with Bonferroni correction. *P* values less than .05 were considered statistically significant.

Results

Temperature and humidity. Temperature and RH ranged from 71.5 °F to 72.2 °F and 49.1% to 63.3%, respectively.

S. cerevisiae. The microbial data for the enumeration of the total number of controlled contaminant, in colony forming units per cubic meter, CFU/m^3, *S. cerevisiae*, revealed statistically significantly fewer microbes ($p < .05$) inside the ICU room than at the point of release in the corridor with the use of both airflow control mechanisms (Figure 3A). Although not statistically significant, the VAV ICU room cultured 19% fewer microbes in the room than at the point of release in the corridor, whereas the Venturi ICU room cultured 33% fewer microbes inside the room than in the corridor.

The total CFU/m^3 inside the room was 12% less with the Venturi system than with the VAV system, though this was not statistically significant ($p = .11$; Figure 3B). Over all experiments, there was no statistically significant difference between CFU/m^3 counts at the point of origin with all samples reaching saturation at 219 CFU/m^3.

Microbes, in CFU/m^3, ranged from 3 to 219 inside the ICU room with the lowest detected CFUs at the beginning and end of each test with VAV and Venturi. The Venturi room CFU counts were statistically significantly cleaner ($p < .05$) than the VAV room counts at the beginning ($T = 0$–8 min) and at the end ($T = 37$–42 min; Table 1).

SF6. The SF6, tracer gas data indicate a significantly lower level of detection inside the ICU room than at the point of origin ($p < .0001$) for both VAV and Venturi controls with 88%

reduction for VAV and Venturi 1 and 87% reduction in contamination for VAV and Venturi 2 and 3 (Figure 4A).

There was no statistical difference in the amount of SF6 at the point of origin between the first VAV and Ventri experiments ($p = .07$) or the second and third ($p = .53$). Venturi airflow control resulted in a average 60.5% and statistically significant reduction in detection as compared to VAV ($p < .05$; Figure 4B).

Transition and stabilization of ACH. The time the VAV and Venturi controls required to transition and stabilize between modes was recorded. From 3 to 6 ACH, the VAV required 41 s, the Venturi required 19 s. From 6 to 15 ACH, the VAV required 72 s, Venturi required 35 s. From 3 to 15 ACH, VAV required 100 s, Venturi required 39 s.

Discussion

In today's healthcare setting, there is an increasing drive to improve patient safety and clinical outcomes while simultaneously reducing the carbon footprint of the care facility, minimizing waste, and preserving financial interest. A properly designed and engineered procedure ready ICU room reduces the necessity to move critically ill patients to the OR by changing the room's environment to mimic the OR's protective environment quickly and effectively. Furthermore, with an airflow control system capable of modulating the amount of air and the pressure relationships when and only when it is necessary, energy and cost are conserved. Specifically, the air changes in the room can be at a minimal set back of 3 ACH when empty and can meet the guideline of 6 ACH when occupied. The space would run at 15 ACH with a positive pressure relationship to the adjacent corridor only for the duration of the emergency procedure, before returning to more efficient lower ACH of a patient room.

In this study, we demonstrated that the contamination originating in the corridor was effectively prevented from detection inside the ICU room by airflow control systems designed to modulate air exchange rates and room pressurization in a critical care space. Both the VAV and the Venturi successfully and significantly reduced the detection of both tracer gas and microbial contaminants as compared to the point of origin in the corridor. Additionally, the airflow system with the quicker response time, Venturi, performed better than VAV at preventing both SF6 and yeast contamination from reaching the patient bed. Seamless transition from unoccupied to occupied to procedure mode facilitated by the Venturi valve system was statistically significantly better at preventing detection of the tracer gas at the patient bed than the more traditional VAV system.

The Venturi system also prevented over 10% more microbial controlled contaminant from being detected inside the room at the patient bed than with the VAV. However, this difference was not calculated to be statistically significant. This data analysis of microbial contamination was limited by sample saturation at the point of origin, as well as several data points within each individual test, rendering a lower sensitivity to the test. On the other hand, when the saturated samples were removed from the data set and VAV was compared to Venturi performance inside the room, Venturi performed 14% better than VAV, but the difference was still statistically insignificant ($p = .1544$).

Conclusions

The modern healthcare environment requires multiuse spaces both to optimize and improve patient care and to reduce overall operational cost. Using the EQI method with a detailed, simulated, realistic testing script in a dynamic environment, this study evaluated the efficacy of creating a "procedure ready" ICU room and compared the efficiency of two airflow control systems, VAV and Venturi valve with respect to contaminant control. The results confirmed that a flexible, multiuse patient critical care room that nimbly transitions from unoccupied to occupied to procedure mode dramatically reduced the contaminants detected in the ICU room as compared to the point of origin in the corridor. Furthermore, the data indicate the Venturi type control system was significantly more effective at preventing infiltration of tracer gas into the ICU room than

the VAV air terminal. This appears to be in part due to the faster transition and stabilization of the Venturi system. Although the results were not statistically significant, the Venturi valve performed approximately 15% better than the VAV at preventing the microbial controlled contaminant from entering the room. Lastly, we estimated the cost saving of a 33% energy reduction using setback results in a monetary savings of US$440.00 to US$841.00 per ICU per year. Further research into the ability of the Venturi to more quickly and effectively change the airflow and pressurize the room is necessary to fully evaluate the effect of this system on biological contaminants.

Implications for Practice

- Treatment or critical care spaces that can accommodate multiple patient conditions can help maximize the utilization of a healthcare facility.
- Increasing asepsis in ICUs may help reduce the risk of infection and/or disease transmission during sterile invasive procedures, for example, resuscitative thoracotomy or central line insertion.
- The ability to utilize a room for multiple treatment or procedures without having to move a critical care need patient or stabilize them for movement provides additional time for direct medical care leading to improved outcomes.
- The ability to quickly positively pressurize the room and increase air change rates provides a protective environment room to treat immune-compromised patients while protecting them from the general patient population.
- The ability to run an unoccupied space at a lower air change rate will save energy and help to contribute to reduced carbon emissions.
- Evidence-based science indicates that quickly cycling into a procedure mode can effectively prevent contaminants from entering the room, thereby protecting vulnerable patients from harmful infectious agents.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research was funded in part by Phoenix Controls, Boston MA.

ORCID iD

Jennifer A. Wagner, PhD, CIC https://orcid.org/0000-0002-2925-3744

References

American Society of Heating, Refrigeration and Air Conditioning Engineers. (2013). *ASHRAE 170-2013*. New York, NY: Author.

Beckman, U. G., Gillie, D. M., Berenholt, S. M., Wu, A. W., & Pronovos, P. (2004, August). Incidents relating to intra-hospital transfer of critically ill patients. *Intensive Care Medicine*, *30*(8), 1579–1585.

Dennis, B. G., & Gunter, O. (2013, May 1). Surgical procedures in the intensive care unit: A critical review. *OA Critical Care*, *1*(1), 6.

Gormley, T. M., Markel, T. A., Jones, H. W., Wagner, J., Greeley, D., Clarke, J. H., … Ostojic, J. (2017). Methodology for analyzing environmental quality indicators in a dynamic operating room environment. *American Journal of Infection Control*, *45*(4), 354–359.

Management, S. O. (1999, March). Guidelines for ICU admission, discharge, and triage. *Critical Care Medicine*, *27*(3), 633–638.

Mirski, M. P., Pandian, V., Bhatti, N., Haut, E., Feller-Kopman, D., Morad, A., Haider, A., … Roberts, V. J. (2012, June). Safety, efficiency and cost-effectiveness of a multidisciplinary percutaneous tracheostomy program. *Critical Care Medicine*, *40*(6), 1827–1834.

Nates, J. L., Nunnally, M., Kleinpell, R., Blosser, S., Goldner, J., Birriel, B., Fowler, C. S., … Sprung, C. L. (2016). ICU admission, discharge and triage guidelines: A framework to enhance clinical operations,

development of institutional polocies and further research. *Critical Care Medicine*, *44*(8), 1553–1602.

Pandian, V. M., Miller, C. R., Mirski, M. A., Schiavi, A. J., Morad, A. H., Vaswani, R. S., . . . Bhatti, N. I. (2012, October). Multidisciplinary team approach in the management of tracheostomy patients. *Otolaryngology and Head and Neck Surgery*, *147*(4), 684–691.

Parmentier-Decrucq, E., Poissy, J., Favory, R., Nseir, S., Onimus, T., Guerry, M. J., . . . Mathieu, D. (2013, April). Adverse events during intrahospital transport of critically ill patients: Incidence and risk factors. *Annals of Intensive Care*, *3*(1), 10.

Winter, M. (2010, May). Intrahospital transfer of critically ill patients; A prospective audit within Flinders Medical Center. *Anaesthesia and Intensive Care*, *38*(3), 545–549.