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Research Article

Quantifying Ventilation Design, Room Layout, and Occupant Activity Parameters during Aerosol-Generating Medical Procedures in Hospitals

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The risk of airborne disease transmission in hospital rooms during aerosol-generating medical procedures is known to be influenced by the size of the room, air ventilation rate, input-to-output flow ratio, vent surface area, and vent location. However, quantitative recommendations for each ventilation design parameter are scarce. Moreover, room layout and occupant activity parameters, such as furniture locations and healthcare worker movement, are often omitted from studies on airborne disease transmission in hospital settings. As a result, the development of policies and technologies aimed at mitigating airborne disease transmission in hospitals has been limited. To address this shortfall, this study is aimed at first characterizing existing ventilation, room layout, and occupancy parameters in hospital rooms where aerosol generation medical procedures (AGMPs) occur and then testing the hypotheses that ventilation, room layout, and occupancy parameters vary significantly between hospital rooms and, in some cases, with time. Information on AGMPs was collected via a survey circulated to healthcare workers within British Columbia's Interior Health Authority (IHA), while hospital room and ventilation system information was collected by reviewing drawing packages of 37 IHA hospital rooms. The survey results indicate that AGMPs commonly occur in trauma, ICU, or general ward rooms with positive or negative pressure ventilation systems. Statistical tests, with room type (trauma, ICU, or general), room pressure (positive or negative), and/or time as independent variables, show that variables relating to ventilation (number of supply vents, supply and exhaust vent location, ventilation rate, and supply and exhaust area) and room layout (congestion score, room volume, light area, and number of lights) vary with room type but not with room pressure. Occupant activity variables (number of workers, number of moving workers, and speed score) also vary with room type, although to differing extent with room pressure and time. The survey and drawing review data presented in this study can help guide systematic comparisons of mitigative technologies as well as parametric investigations on how room layout, ventilation, and operational parameters influence airborne disease spread. This is a crucial first step in achieving quantitative and clinically relevant recommendations for mitigating airborne disease transmission in healthcare settings.

1. Introduction

Despite extensive preventative measures implemented globally, COVID-19 infected over 768 million people, resulting in over 6 million deaths as of July 19, 2023 [1]. From January 2020 to March 2022, the total cost of COVID-19-related hospitalizations in Canada exceeded $4 billion [2]. COVID-19 is dangerous and costly because—like other airborne diseases such as influenza, measles, and tuberculosis (TB)—it spreads very quickly and is difficult to contain, especially in healthcare settings [3]. In response to the COVID-19 pandemic, several publications in support of new indoor infection prevention technologies were released [4–6]. However, Thornton et al. [7] concluded that very few studies quantify ideal indoor ventilation parameters after summarizing 32 studies related to ventilation design and the spread of

coronaviruses. Other sources report that increasing the room ventilation rate decreases the risk of viral infection [5, 8–21]. However, increased ventilation rate may not help prevent infection for those working in proximity to the infector [8]. Indeed, increased ventilation rate and poorly controlled input-to-output flow ratios can lead to a wider spread of the virus [5, 16, 22, 23]. Moreover, strategic placement of supply and exhaust vents can mitigate disease spread, while improper air flow pattern design can lead to high viral concentrations in certain areas of each room [16, 24]. While ventilation rate, input-to-output flow ratio, and vent layouts play a significant role in airborne disease transmission, quantitative recommendations on each variable are scarce. As a result, mitigative policy and technology development have been limited.

Medical procedures that generate aerosols or droplet nuclei in high concentration are called aerosol-generating medical procedures (AGMPs) and increase the risk of airborne disease transmission [25]. Endotracheal intubation, positive pressure ventilation, and high-flow supplemental oxygen are all examples of AGMPs that result in different infectious emission rates [25, 26]. Vancouver Coastal Health's Best Practice Guideline for AGMPs states that AGMPs should be performed in private rooms with N95 respirators, face shields, and other personal protective equipment (PPE) whenever possible [25]. However, ideal rooms and PPE are not always available due to limited resources and the clinical urgency of the AGMP. Procedure acuity, and therefore occupant activity, can vary greatly with the type of hospital room in which the AGMP is performed. Occupant activity can significantly disrupt airflow patterns of common ventilation designs [27–33]. Human thermal plumes (HTPs) can produce airflows on the same order of magnitude as supply vents, disrupting ventilation systems [30, 31, 33]. Saarinen et al. [32] demonstrated that human movement through the doors of a negative pressure room can result in containment failure, but no ventilation system was included in their simulations. Another simulation showed that even at a room ventilation rate of 61 air changes per hour (ACH), human movement can disrupt the air flow pattern in healthcare settings [28]. Although the importance of occupant activity has been established, studies showing the effectiveness of new mitigative technologies frequently omit occupant movement [4–6]. Of the 32 studies reviewed by Thornton et al. [7], eight presented computer simulation results for airborne disease distribution in hospital settings, but none included human movement. Furthermore, none of the hospital-based computer simulation studies reviewed by Thornton et al. [7] evaluated infection risk during AGMPs specifically; infectious emissions were modeled as coughs, "puffs," or other common respiratory patterns [5, 13, 16, 20, 22, 23, 34, 35].

Room layout parameters are often neglected or held constant in airborne disease studies as well. For example, of the eight hospital simulation studies reviewed by Thornton [7], only two included equipment other than hospital beds. Anghel et al. [34] included a table and Li et al. [23] included lights as heat sources. None of the previously referenced studies that highlight the effectiveness of new mitigative technologies included hospital equipment other than hospital beds [4–6]. Additionally, of the seven previously referenced studies that explored the influence of occupant activity, only two included equipment other than hospital beds [28, 29]. Real hospital rooms where AGMPs occur commonly contain large cabinets, monitors, carts, and other furniture that may block vents and walking paths and therefore may significantly influence air flow patterns.

A common limitation of past work related to airborne disease spread in healthcare settings is that individual experiments and simulations involve a relatively narrow range of clinical settings. As a result, the variation and relative influence of room/furniture layout, ventilation system design, and clinical operational parameters are unclear. The objectives of this study are to (1) characterize existing ventilation, room layout, and occupancy parameters and (2) test the hypotheses that ventilation, room layout, and occupancy parameters vary significantly between hospital rooms and, in some cases, with time. The data presented in this study will allow for systematic comparisons of mitigative technologies and parameters that significantly influence airborne disease spread by using design of experiment (DOE) methodology. This is a crucial first step in achieving quantitative and clinically relevant recommendations for ideal ventilation designs in healthcare settings.

2. Materials and Methods

To collect data related to ventilation design and room layout parameters, we reviewed hospital drawings and air balancing data sheets. We then surveyed clinicians to collect data related to room congestion and occupancy parameters. Finally, we performed statistical analyses to estimate 95% confidence intervals for these parameters and test the hypotheses that they differed with hospital room type and room pressure and, in some cases, with time.

Room type refers to the location and overall design of a hospital room. For example, trauma rooms, intensive care unit (ICU) ward rooms, and general ward rooms are all room types located in different hospital departments where different staff and equipment are available. Room pressure can be either positive or negative. In a negative pressure room, the exhaust vent flow rate is greater than the supply vent flow rate to keep contaminants from escaping the room. In a positive pressure room, air and contaminants can be pushed out of the room through doorways, windows, etc. The specific ventilation design, room layout, and occupant activity variables quantified herein are defined in the following subsections. Additionally, data collection methods for each variable are described in more detail.

2.1. Hospital Drawing Review for Ventilation Design and Room Layout Parameters. Data for all ventilation design parameters were collected by reviewing hospital drawing packages provided by the Interior Health Authority (IHA), a regional health authority in the southern interior region of British Columbia, Canada. Detailed schematics of different hospital rooms ($n = 37$) from 15 different cities within IHA were reviewed. Quantitative ventilation design parameters

recorded during the hospital drawing review process include ventilation rate, input-to-output flow ratio, supply vent area, exhaust vent area, supply vent count, and exhaust vent count. Flow rates through each vent were found using the air balancing data sheets of each hospital. Ventilation rates were calculated by dividing the summed supply or exhaust vent flow rate, whichever was larger, by the room volume. Input-to-output flow ratios were calculated by dividing the total supply vent flow rate by the total exhaust vent flow rate in each room. In most cases, the supply and exhaust vent dimensions were listed on HVAC schematics. The measurement tool in Adobe Acrobat Pro DC ver. 2020.013.20074 was used to obtain vent areas from reflected ceiling schematics in cases where dimensions were not listed. Vent areas are recorded in square meter without including the diffuser perforation fraction. In other words, the total ceiling or wall area covered by each vent was recorded, and multiplication by a perforation fraction is needed to obtain the air flow area.

Supply and exhaust vent locations were qualitatively recorded during the drawing review and are treated as categorical variables in subsequent statistical tests. Supply vent locations were categorized as "scattered" when multiple supply vents were evenly spread on the room's ceiling, or as "grouped" when all supply vents were located above the patient's bed. Similarly, exhaust vent locations were categorized as "wall scattered" when multiple low-level exhausts were evenly spread on the room's walls, as "wall grouped" when all exhausts were low-level and on a single side of the room, or as "high-level" when all exhausts were on the ceiling or near ceiling height. In Figure 1(a), "grouped" and "wall grouped" supply and exhaust vent locations are shown. In contrast, "scattered" and "wall scattered" supply and exhaust vent locations are shown in Figure 1(b). Ventilation systems are commonly categorized as displacement, downward, or mixing ventilation designs [29–31]. Both vent layouts shown in Figure 1 are considered downward ventilation; however, there were clear differences in vent locations and number of vents even though each room is of similar size. As such, vent area, count, and locations were recorded as unique variables in this study rather than using the broader categorizations of downward, mixing, and displacement ventilation.

Room layout parameters in this study include room air volume, ceiling height, room shape (elongation), light area, number of lights, and congestion score. Except for congestion score, all room layout parameters were collected in the drawing review process. Room dimensions were found using Adobe's measurement tool on scaled architectural schematics. In most cases, light dimensions were listed on electrical schematics. Adobe's measurement tool was used to obtain light areas from reflected ceiling schematics in cases where dimensions were not listed.

The elongation of each room's floor layout was calculated to quantify overall room shape. Following the method described by Wirth [36], elongation is found by drawing a bounding box around the shape of interest and then dividing the smaller bounding box dimension by the larger one. Moving forward, the elongation of each room's floor layout is referred to as the wall aspect ratio. There are several ways to define shape; however, with the wall aspect ratio, ceiling height, and room volume, a rectangular prism of similar overall shape as the actual room can be formed while preserving the real floor area.

Smaller particles rise with HTPs and may eventually recirculate in the room with the ventilation system flow. The likelihood of recirculating is probably affected by ceiling height and light area/count. Rooms where AGMPs occur typically have large cabinets or other pieces of equipment blocking exhaust vents. The amount of furniture in hospital rooms was quantified with congestion scores collected through the clinician survey using a scoring metric defined in the following section. Many simulation studies related to airborne disease in healthcare settings focused on a single room (and therefore a single room volume, ceiling height, and wall aspect ratio) [5, 6, 16, 27–31, 34]. To overcome this gap in the literature, room layout parameters were quantified in this study.

2.2. Clinician Survey and Occupant Activity Parameter Definitions. The occupant activity parameters during AGMPs quantified in this study were number of workers, number of moving workers, movement speed, procedure duration, and respiratory support. Data for all occupant activity parameters and room congestion was collected through a clinician survey circulated with approval from the IHA and the University of British Columbia's Research Ethics Board. After receiving informed consent from each participant, survey responses from 38 ($n = 38$) different doctors, registered nurses, or respiratory therapists were collected using Qualtrics software, version 072023, copyright © 2023. Qualtrics and all other Qualtrics product or service names are registered trademarks or trademarks of Qualtrics, Provo, UT, USA. Before asking the survey participants any questions, the categorical variables "room type" and "room pressure" were defined as previously described. To ensure consistent results were collected, the following typical stepwise intubation procedure was defined for survey participants and "intubation step" was included as a categorical variable to reflect variations in time:

Intubation steps:

(1) Patient positioning and other intubation preparation

(2) Preoxygenation

(3) Drug administration to make the patient lose respiratory drive

(4) Laryngoscopy and intubation

(5) Confirmation of endotracheal tube placement

(6) Ventilator attachment and post intubation care

Endotracheal intubation was chosen as the AGMP of interest because it is considered a high-risk AGMP [25], and multiple other AGMPs, such as high-flow nasal cannula (HFNC) and continuous positive airway pressure (CPAP), are known to occur before and after the physical intubation. By asking each survey participant about the same predefined

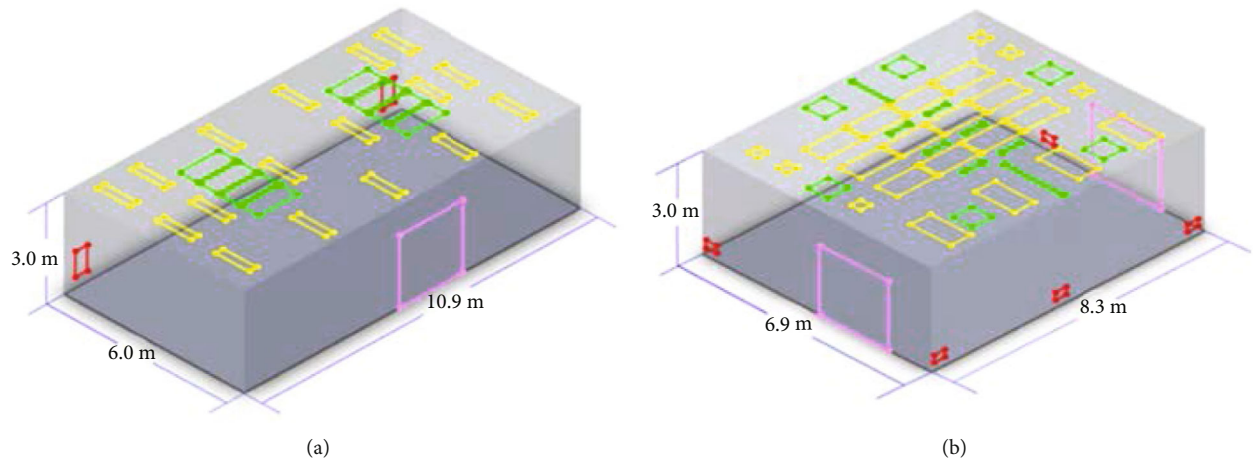

Figure 1: Sample schematics of hospital room layout, lighting, and ventilation system design for trauma rooms in (a) Kelowna General Hospital and (b) Royal Inland Hospital. Yellow: lights; green: supply vents; red: exhaust vents; pink: doors.

intubation procedure, consistent results relevant to several AGMPs were collected at once.

Once each categorical variable was defined, survey participants were asked which rooms they have performed or assisted with intubation in and to specify every occupant activity parameter and room congestion score for each room where they have completed an intubation. See Figure 2 for a depiction of the questionnaire process and Supplementary Material (available here) for the full questionnaire.

In the "procedure distribution" step of the survey, respondents indicated that endotracheal intubations may occur in trauma, ICU, or general ward rooms with positive or negative pressure ventilation systems. The congestion and speed scoring charts provided to survey participants are shown in Tables 1 and 2. Ordinal scales are commonly used to quantify qualitative modalities [37–40]. Furthermore, Syddall et al. [40] concluded that self-reported walking speed is a good marker of measured walking speed.

Participants were also asked to indicate which respiratory support systems are active during each step of a typical intubation by filling out the boxes shown in Figure 3. The example response in Figure 3 indicates that low-flow supplemental oxygen was active during step 1 in 50% of the intubations performed by this individual. Participants filled out the same respiratory support table for each intubation step.

2.3. Statistical Methods. All statistical analyses were conducted using IBM SPSS Statistical software (version 28.0.1.1) under the assumption that independent cases were observed. A threshold significance value of 0.05 was used in all statistical tests. Data from 37 different hospital rooms and 38 survey responses were included in the statistical tests. This was the maximum number of samples that could be collected due to limited clinician time, access to hospital rooms, and project budget. Using G*Power software (version 3.1.9.7), an a priori statistical power was estimated to be 0.85, assuming a "large" effect size of 0.5 [41–43].

Data from each dependent variable was tested for normality using a Kolmogorov-Smirnov test. Levene's test was conducted on each data set to check for homogeneity of variances as well. In all cases, the normality and/or homogeneity assumptions were violated, and so nonparametric mean comparison tests were used moving forward. Using nonparametric tests preserved the ordinal nature of the congestion and speed scores [44, 45].

The chosen mean comparison test for each combination of independent and dependent variables was dictated by the number of independent variable groups and the type of dependent variable being tested. Room type, room pressure, and intubation step are all categorical independent variables with three, two, and six possible categories, respectively. Supply and exhaust vent locations are categorical dependent variables, but all other dependent variables are quantitative. When both the independent and dependent variables were categorical, Fisher's exact test was used. When the dependent variable was quantitative, a Mann–Whitney test was used if the independent variable only had two categories (room pressure), but a Kruskal-Wallis test was conducted if more than two independent variable categories were present (room type or intubation step). In cases where significant differences were found in tests with more than two independent variable categories, post hoc pairwise comparisons were used to test for differences between specific groups. All ventilation design and room layout parameters were assumed to be constant with time, so only occupant activity variables were tested against intubation step.

3. Results

Significance values, sorted based on parameter type (ventilation design, room layout, and occupant characteristics), for each mean comparison (room type, room pressure, and intubation step where relevant), are shown in Tables 3–5. Number of exhaust vents, ceiling height, wall aspect ratio, and procedure duration did not show significant differences with respect to room type or room pressure and were assumed to be constant with time (intubation step). Therefore, post hoc tests were not performed on these parameters. Dependent variables that showed significant differences with

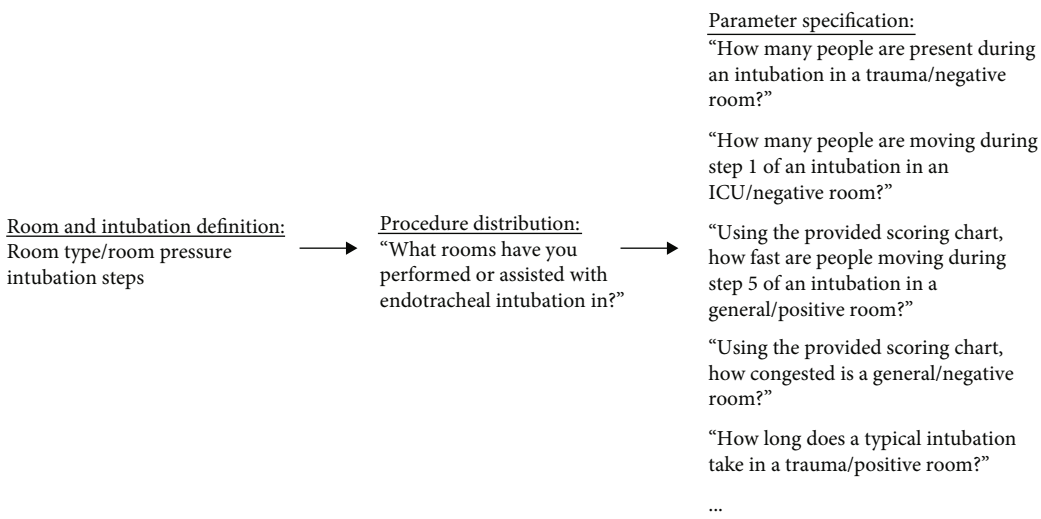

Figure 2: Survey flow chart.

Table 1: Congestion score descriptions.

1 Very spacious	3 Spacious	5 Congested	7 Very congested
(i) Little to no large pieces of equipment.	(i) Some large pieces of equipment.	(i) Full of large pieces of equipment.	(i) Packed with large pieces of equipment.
(ii) The equipment is well spaced out and organized.	(ii) The equipment is well spaced out and organized.	(ii) Equipment is more densely packed.	(ii) No additional equipment could fit in the room.
(iii) People walking in the room have plenty of space to distance from others.	(iii) People walking in the room have some room to distance from others.	(iii) People can walk through/around the room, but distancing is difficult due to limited walking paths.	(iii) Walking through/around the room without bumping into something is difficult.

Table 2: Speed score descriptions.

1 Very low speed	3 Low speed	5 High speed	7 Very high speed
(i) Nobody walks through/ around the room.	(i) Movement speed is low, no more than a casual stroll.	(i) Movement speed is somewhat faster, but still a walk.	(i) Movement speed is approaching more of a run/jog.

	Intubation step 1
Low flow supplemental oxygen	50
High flow supplemental oxygen	20
CPAP/BiPAP	10
Bag-value-mask	0
No support system	20
Other	0
Total	100

Figure 3: Example respiratory support frequency response on Qualtrics for intubation step 1.

Table 3: Mean comparison significance values for ventilation design parameters.

Dependent variable	Independent variable	
	Room type	Room pressure
Number of supply vents	<0.001*	0.126
Exhaust vent location	<0.001*	0.129
Ventilation rate	0.002*	0.150
Supply area	0.003*	0.199
Exhaust area	0.004*	0.159
Supply vent location	0.005*	0.714
Number of exhaust vents	0.072	0.111
Input-to-output flow ratio	0.805	<0.001*

Mean comparisons where significant differences were found are marked with *.

Table 4: Mean comparison significance values for room layout parameters.

Dependent variable	Independent variable	
	Room type	Room pressure
Congestion score	<0.001*	0.849
Room volume	<0.001*	0.641
Light area	<0.001*	0.916
Number of lights	0.008*	0.461
Wall aspect ratio	0.175	0.685
Ceiling height	0.140	0.538

Mean comparisons where significant differences were found are marked with *.

Table 5: Mean comparison significance values for occupant activity parameters.

Dependent variable	Independent variable		
	Room type	Room pressure	Intubation step
Number of workers	<0.001*	0.003*	0.554
Number of moving workers	<0.001*	<0.001*	<0.001*
Speed score	<0.001*	0.665	<0.001*
Procedure duration	0.156	0.233	—

Mean comparisons where significant differences were found are marked with *.

respect to at least one independent variable are discussed further in the subsequent sections.

3.1. Ventilation Design. Except for the number of exhaust vents and input-to-output flow ratio, all ventilation design parameters varied with room type. The only ventilation parameter that varied with room pressure was input-to-output flow ratio, which is expected because input-to-output flow ratio dictates room pressure. General ward rooms had significantly lower ventilation rates than ICU ($p = 0.008$) and trauma ($p = 0.004$) rooms. Significant differences were not found when comparing ventilation rates between trauma and ICU rooms ($p = 0.999$). Trauma rooms had significantly larger supply vent area, supply vent count, and exhaust vent area relative to ICU ($p \leq 0.021$) and general ward ($p \leq 0.004$) rooms. The supply vent area, supply vent count, and exhaust vent area did not vary significantly between ICU and general ward rooms ($p \geq 0.241$).

Figure 4 shows 95% confidence intervals for each quantitative ventilation parameter normalized by their respective overarching means. The independent variable groupings shown for each dependent variable also reflect where significant differences were found. For example, it was determined that general ward room ventilation rates are significantly different than trauma and ICU ventilation rates, so a separate ventilation rate confidence interval is shown for general ward rooms. Furthermore, the ventilation rate confidence intervals were normalized by 16.7 ACH, which is the mean ventilation rate across all data sets. The remaining mean values used for normalization were 1.27 m^2 for supply vent area, 0.198 m^2 for exhaust vent area, 2.43 for number of supply vents, and 1.78 for number of exhaust vents. A single confidence interval is shown for the number of exhaust vents because no significant differences were found in mean comparison tests.

Both supply vent location and exhaust vent location differed between trauma and ICU rooms and trauma and general rooms ($p \leq 0.024$). Supply vent location and exhaust vent location did not differ between ICU and general rooms ($p \geq 0.215$). Trauma room supply and exhaust vent locations were somewhat evenly split between "grouped" and "scattered," and "wall grouped" and "wall scattered," with ratios of 4 : 7 in both cases. Of the 11 trauma rooms included in this study, none had "high-level" exhausts. "Grouped" supply vent locations are much more likely in ICU and general rooms with a grouped-to-scattered ratio of 23 : 3. "Wall grouped" and "high-level" exhaust locations were common among ICU and general ward rooms; however, only one of the 26 ICU or general ward rooms had "wall scattered" exhausts. The overall ratio of "wall grouped," "wall scattered," and "high-level" exhaust locations for ICU and general ward rooms was 11 : 1 : 14. Vent location types did not vary with room pressure.

Table 6 provides a summary of the ventilation design parameter confidence intervals and lists the common groups for each categorical dependent variable (vent locations). The column headings in Table 6 vary to reflect the significant differences found in each mean comparison test. These descriptive statistics will allow future researchers to conduct screening and optimization studies on a clinically relevant range of ventilation parameters in rooms where AGMPs commonly occur.

3.2. Room Layout. Congestion score, room volume, light area, and number of lights all varied by room type ($p \leq 0.008$). We found no association between room type and either of wall aspect ratio or ceiling height. Lastly, we did not find an association between any room layout variables and room pressure.

The average congestion score across all room types was 5, indicating that all rooms were densely packed with large equipment. Mean congestion scores varied between all three room types ($p \leq 0.017$). Trauma room volume exceeded ICU ($p = 0.021$) and general ($p < 0.001$) room volumes in pairwise comparisons, but general and ICU room volumes were not significantly different ($p = 0.205$). Regarding lighting versus room type, trauma rooms had the largest mean light area and number of lights ($p \leq 0.06$). Significant differences were not found when comparing ICU and general room light area and light count ($p \geq 0.135$).

Figure 5 shows 95% confidence intervals for each room layout parameter normalized by their respective overarching means, while Table 7 provides nominal (unnormalized) values for each confidence interval. The independent variable groupings shown for each dependent variable also reflect where significant differences were found. The mean values used for normalization were 5 for congestion scores, 67 m^3 for room air volume, 2.5 m^2 for light area, 6.1 for

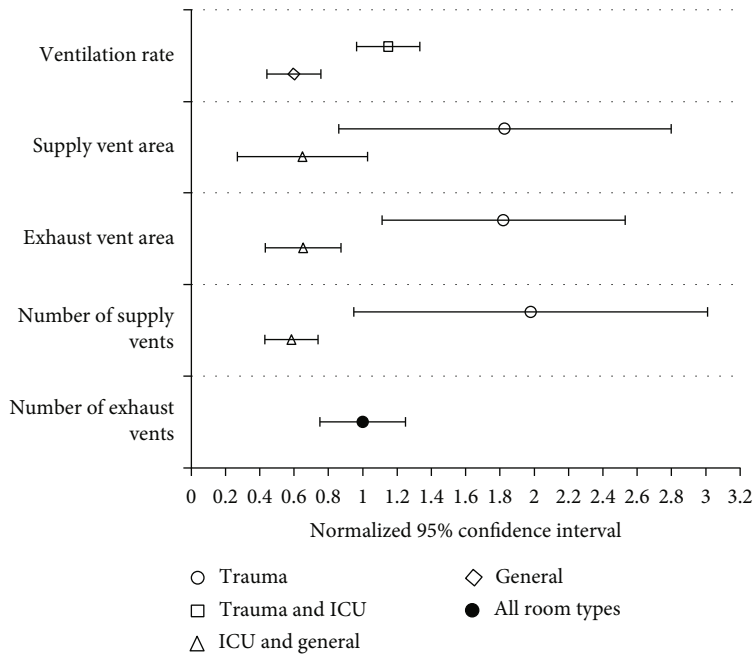

Figure 4: Normalized 95% confidence intervals for each quantitative ventilation design parameter. Markers represent mean values within each independent variable grouping. For each dependent variable, the displayed independent variable groupings reflect where significant differences were found. Each confidence interval was normalized by the overarching mean value of each complete dependent variable data set: 16.7 ACH, 1.27 m^2, 0.198 m^2, 2.43, and 1.78 for ventilation rate, supply vent area, exhaust vent area, number of supply vents, and number of exhaust vents, respectively.

Table 6: Ventilation parameter summary. Nominal 95% confidence intervals are provided for each quantitative parameter. Integer values are provided for discrete dependent variables. Common groups of each categorical dependent variable are listed. Column headings vary to reflect significant differences found in each mean comparison test.

Dependent variable	Trauma and ICU	General
Ventilation rate (ACH)	19.2 ± 3.35	9.99 ± 2.62
Dependent variable	Trauma	ICU and general
Supply area (m^2)	2.32 ± 1.22	0.82 ± 0.44
Exhaust area (m^2)	0.36 ± 0.14	0.13 ± 0.04
Number of supplies	2 to 7	1 or 2
Supply locations	Grouped or scattered	Grouped
Exhaust locations	Wall grouped or wall scattered	Wall grouped or high-level
Dependent variable	Positive pressure	Negative pressure
I/O flow ratio	1.17 ± 0.065	0.83 ± 0.07
Dependent variable	All room types and pressures	
Number of exhausts	1 or 2	

number of lights, 0.8 for wall aspect ratio, and 2.61 m for ceiling height. A single confidence interval is shown for wall aspect ratio and ceiling height because no significant differences were found in these mean comparison tests.

3.3. Occupant Activity. Procedure duration did not vary with room type or room pressure ($p \geq 0.156$). The 95% confidence interval for procedure duration across all room types and pressures was 23.9 ± 2.9 minutes. The number of workers varied with room type and room pressure ($p \leq 0.003$) but not with intubation step ($p = 0.554$). This implies that no person enters or exits the room during a given intubation procedure, and the number of workers can be treated as a constant for each room type and room pressure. The mean number of workers present in a trauma/positive or an ICU/positive room was four. On average, three workers were present in a trauma/negative or an ICU/negative room. Five workers were present on average in general ward rooms.

Regarding the number of moving people, significant differences were present between room types, room pressures, and intubation steps ($p < 0.001$). No significant differences were found between trauma and ICU negative

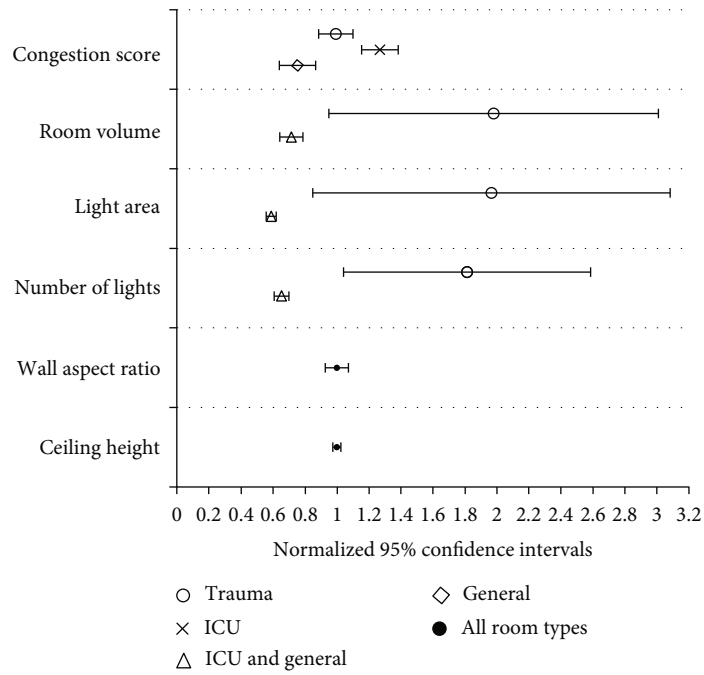

Figure 5: Normalized 95% confidence intervals for each room layout parameter. Markers represent mean values within each independent variable grouping. For each dependent variable, the displayed independent variable groupings reflect where significant differences were found. Each confidence interval was normalized by the overarching mean value of each complete dependent variable data set: 5, 67 m^3, 2.5 m^2, 6.1, 0.8, and 2.61 m for congestion scores, room air volume, light area, number of lights, wall aspect ratio, and ceiling height, respectively.

Table 7: Room layout parameter summary. Nominal 95% confidence intervals are provided for each quantitative parameter. Integer values are provided for discrete dependent variables. Common groups of each categorical dependent variable are listed. Column headings vary to reflect significant differences found in each mean comparison test.

Dependent variable	Trauma	ICU	General
Congestion score	4.9 ± 0.5	3.7 ± 0.5	6.3 ± 0.6
Dependent variable	Trauma	ICU and general	
Room volume (m^3)	112 ± 34	48 ± 4	
Light area (m^2)	4.90 ± 2.8	1.47 ± 0.07	
Number of lights	6 to 16	4	
Dependent variable	All room types and pressures		
Wall aspect ratio	0.80 ± 0.05		
Ceiling height (m)	2.61 ± 0.06		

Table 8: Number of moving workers sorted by room type, room pressure, and intubation step.

	Movement pattern A: trauma/positive, ICU/positive, and general rooms	Movement pattern B: trauma/negative and ICU/negative rooms
	Number of moving workers	Number of moving workers
Step 1	3	2
Step 2	2	2
Step 3	2	1
Step 4	2	1
Step 5	2	2
Step 6	2	2

pressure rooms ($p \geq 0.999$); however, these two rooms varied from all remaining room type and pressure combinations ($p \leq 0.042$). Trauma and ICU positive pressure rooms and both general ward rooms had a similar number of moving people ($p \geq 0.132$). To summarize the post hoc test results for the number of moving people, two movement patterns were defined: movement patterns A and B. Each "movement pattern" is defined in Table 8. Within each movement pattern, significant differences exist between intubation steps where integer values in Table 8 vary ($p \leq 0.019$). During a typical intubation procedure, at least one person is moving at all times.

Speed scores varied with room type and intubation step ($p < 0.001$), but not room pressure ($p = 0.665$). Post hoc tests revealed that speed scores were similar between trauma and general ward rooms ($p = 0.08$). However, ICU room speed scores were significantly different than trauma and general rooms ($p < 0.001$). These differences are reflected in the "speed patterns" defined in Table 9. Within each speed pattern, significant differences exist between intubation steps where confidence intervals in Table 9 do not overlap ($p \leq 0.008$).

Table 9: 95% confidence intervals for movement speed score during each intubation step.

	Speed pattern A: trauma and general rooms Speed score (/7)	Speed pattern B: ICU rooms Speed score (/7)
Step 1	4.80 ± 0.30	3.89 ± 0.41
Step 2	3.71 ± 0.36	3.02 ± 0.37
Step 3	3.24 ± 0.38	2.32 ± 0.44
Step 4	2.75 ± 0.44	1.89 ± 0.44
Step 5	3.07 ± 0.36	2.59 ± 0.41
Step 6	3.63 ± 0.33	3.23 ± 0.35

In Table 10, the average respiratory support frequency recorded among all survey participants is shown for each intubation step. Intubation step 6 was omitted from the table because connection to a mechanical ventilator is implied. All participants who put a nonzero value in the "other" respiratory support column specified that they were referring to a mechanical ventilator. Due to survey time constraints, participants were not asked if active respiratory supports varied between rooms. Table 10 represents the average respiratory support frequencies for intubation procedures in all defined rooms, but this does not mean that respiratory support frequencies are independent of room type and pressure. An occupant activity parameter summary is provided in Table 11.

4. Discussion

Quantitative recommendations for ventilation design parameters in hospital settings are scarce, and a relatively narrow range of hospital ventilation parameters have been tested in studies related to ventilation design and the spread of coronaviruses [7]. Additionally, room layout parameters are often neglected or held constant in airborne disease studies [4–7, 23, 28, 29, 35]. The average congestion score across all rooms was 5, indicating that all rooms were densely packed with large equipment and neglecting to include large pieces of equipment that may be a detrimental factor of past studies. The results in Tables 6 and 7, especially the large variations within trauma room data sets, emphasize the need for systematic screening and optimization studies on a clinically relevant range of ventilation design and room layout parameters.

Interestingly, ICU room volumes, supply areas, exhaust areas, light areas, supply counts, and light counts were similar to that of general ward rooms, while ICU ventilation rates were similar to that of trauma rooms. This suggests that trauma rooms can be handled as scaled-up versions of ICU rooms when considering these variables in modeling. For instance, for a room with baseline ICU characteristics, if the size, supply area, exhaust area, etc. are tripled while the ventilation rate, wall aspect ratio, and ceiling height are held constant, a room with trauma room characteristics would be formed. On the other hand, to create a general ward room, the ventilation rate of an ICU room could simply be lowered. Working outwards from these baseline rooms, occupant activity, input-to-output flow ratio, vent locations, and room congestion could be manipulated with room type and pressure in future models. This is an example of how the presented data can simplify the implementation of clinical parameters into computer models.

Input-to-output flow ratio, number of exhaust vents, wall aspect ratio, ceiling height, and procedure duration were the only variables that did not vary with room type. An approximately equal number of positive and negative pressure rooms were included for each room type, which is likely why input-to-output flow ratios did not vary. The ratio of positive to negative pressure rooms among trauma, ICU, and general ward rooms was 7 : 4, 7 : 9, and 1 : 1, respectively. These ratios reflect what rooms are available in IHA and were not chosen deliberately. The number of exhaust vents did not vary with room type either. It was uncommon for any room to have more than 2 exhausts. Some of the larger trauma rooms had 8 supply vents, but still only 2 exhausts. Qian et al. [30] reported only small changes in personal exposure indices when the number of exhausts changed between 1 and 4. However, no moving people were included in this study. In more realistic cases where mixing is enhanced by the motion of occupants, the number of exhaust vents may be more influential, perhaps justifying an increase in the number of exhaust vents in future hospital designs. The ceiling height and room shape likely did not vary with room type because the room types included in this study do not require particularly large or oddly shaped pieces of equipment that may require higher ceilings or longer walls. Lastly, even though the number of workers and their movement speeds varied between each room type, the overall procedure duration did not. AGMPs are supposed to occur in private rooms [25]. Perhaps when an intubation unexpectedly occurs in a general wardroom or trauma room, more staff and higher movement speeds are present to ensure that the procedure is completed in a reasonable time.

Of the eight studies reviewed by Thornton et al. [7] that represent airborne disease distribution in hospital settings, none included human movement. However, results from this study indicated that at least one healthcare worker is always moving during the AGMP of interest. Interestingly, ICU speed scores were lower than those of trauma and general rooms. This may be because ICU rooms are more congested with large pieces of equipment (Figure 5). Furthermore, none of the hospital-based computer simulation studies reviewed by Thornton et al. [7] evaluated infection risk during AGMPs specifically, and so infectious emissions were modeled as coughs, "puffs," or other more common respiratory patterns [5, 13, 16, 20, 22, 23, 34, 35]. The data in Tables 8–11 allows future researchers to include clinically relevant human movement patterns and infectious emission rates in studies focused on AGMPs.

The descriptive statistics presented in Tables 6, 7, and 11 allows researchers to target specific rooms where AGMPs occur in future studies with clarity on the range of clinically relevant conditions. The sensitivity of new mitigative

Table 10: Active respiratory support systems during each step of intubation.

	High-flow supplemental oxygen	Low-flow supplemental oxygen	Bag valve mask	CPAP/BiPAP	No support	Other
Step 1	32%	32%	16%	16%	0%	0%
Step 2	38%	11%	38%	11%	0%	0%
Step 3	16%	16%	50%	16%	0%	0%
Step 4	9%	9%	32%	9%	32%	9%
Step 5	5%	5%	39%	5%	5%	39%

Table 11: Occupant activity parameter summary. Column headings vary to reflect significant differences found between room type and room pressure. Readers are directed to movement and speed pattern tables to see variations with intubation step.

Dependent variable	All room types and pressures				
Procedure duration (minutes)	23.9 ± 2.9				
Dependent variable	Trauma/positive	Trauma/negative	ICU/positive	ICU/negative	General/positive General/negative
Number of workers	4	3	4	3	5 or 6
Movement pattern (Table 8)	A	B	A	B	A
Speed pattern (Table 9)	A	A	B	B	A

technologies or policies to the variable conditions encountered in clinical settings can also be evaluated using the descriptive statistics by randomizing room parameters within their respective 95% confidence intervals.

4.1. Study Limitations. All survey responses were collected from healthcare professionals working within the IHA. Moreover, all reviewed drawing packages represented hospitals within the IHA. Hospital rooms and procedures may vary significantly with geographical location and across health authorities, so similar parameter definition studies should be conducted in other regions. Furthermore, only single-bed general ward rooms were included. This study focused on AGMPs, which more frequently occur in single-bed general ward rooms over multibed rooms. However, AGMPs still occasionally occur in multibed general ward rooms, and more general airborne disease spread studies should include data from these rooms.

Within the IHA, hospitals are tiered from smallest to largest as community, regional, or tertiary. While hospital tier was not included as an independent variable in this study due to limited samples, hospital tier may be linked to larger trauma room parameter variations. For example, the average volume among the community hospital trauma rooms included in this study was $83\,m^3$, but the average was $130\,m^3$ for the regional and tertiary trauma rooms. In contrast, ICU and general wardrooms are much smaller than trauma rooms and seem to be less affected by the hospital tier. In future studies, hospital tier should be included as an independent variable.

Temperature and relative humidity (RH) are known to influence indoor airborne disease transmission [46–50]; however, ranges for these variables were not included in this study due to anticipated seasonal changes. Interaction effects between the studied variables, temperature, and RH should be explored in future studies. For example, temperature and RH could be included as noise variables randomized within common ranges for indoor spaces.

5. Conclusion

Quantitative recommendations for ventilation design parameters to reduce the risk of airborne disease transmission in hospitals are scarce. Room layout and occupant activity parameters are often neglected in airborne disease studies in hospital settings. As a first step towards achieving quantitative recommendations for ventilation design parameters and mitigative solutions for airborne disease spread in healthcare settings, a survey was circulated to healthcare workers within the Interior Health Authority (IHA), and IHA hospital drawing packages were reviewed to quantify the range of clinical conditions necessary to simulate airborne disease spread in healthcare settings. Mean comparison tests revealed that many of the ventilation design, room layout, and occupant activity parameters varied with room type, room pressure, and time. Descriptive statistics for each parameter are presented and sorted based on where significant differences were found. Using the data presented in this study, quantitative and clinically relevant recommendations for ideal ventilation designs in healthcare settings can be achieved in future work.

Data Availability

Survey and drawing review data is available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Supplementary Materials

The full questionnaire is provided as a supplementary document. *(Supplementary Materials)*

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