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REPORTS OF ORIGINAL INVESTIGATIONS

Association of intensive care unit occupancy during admission and inpatient mortality: a retrospective cohort study

Association entre le taux d'occupation à l'unité de soins intensifs pendant l'admission et la mortalité hospitalière: une étude de cohorte rétrospective

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Abstract

Purpose *There is conflicting evidence regarding the influence of intensive care unit (ICU) occupancy at the time of admission on important patient outcomes such as mortality. The objective of this analysis was to characterize the association between ICU occupancy at the time of ICU admission and subsequent mortality.*

Methods *This single-centre, retrospective cohort study included all patients admitted to the ICU at the Vancouver General Hospital between 4 January 2010 and 8 October 2017. Intensive care unit occupancy was defined as the number of ICU bed hours utilized in a day divided by the total amount of ICU bed hours available for that day. We constructed mixed-effects logistic regression models controlling for relevant covariates to assess the impact of admission occupancy quintiles on total inpatient (ICU and ward) and early (72-hr) ICU mortality.*

Results *This analysis included 10,365 ICU admissions by 8,562 unique patients. Compared with ICU admissions in the median occupancy quintile, admissions in the highest and second highest occupancy quintile were associated with a significant increase in the odds of inpatient mortality (highest: odds ratio [OR], 1.33; 95% confidence interval [CI], 1.12 to 1.59; P value < 0.001; second highest: OR, 1.21; 95% CI, 1.02 to 1.44; P value < 0.03). No association between admission occupancy and 72-hr ICU mortality was observed.*

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Conclusions *Admission to the ICU on days of high occupancy was associated with increased inpatient mortality, but not with increased 72-hr ICU mortality. Capacity strain on the ICU may result in significant negative consequences for patients, but further research is needed to fully characterize the complex effects of capacity strain.*

Résumé

Objectif *Les données probantes concernant l'influence du taux d'occupation à l'unité de soins intensifs (USI) lors de l'admission sur d'importants pronostics de patients tels que la mortalité sont conflictuelles. L'objectif de cette analyse était de caractériser l'association entre le taux d'occupation de l'USI au moment de l'admission à l'USI et la mortalité subséquente.*

Méthode *Cette étude de cohorte rétrospective monocentrique a inclus tous les patients admis à l'USI à l'Hôpital général de Vancouver entre le 4 janvier 2010 et le 8 octobre 2017. Le taux d'occupation de l'unité de soins intensifs était défini comme le nombre d'heures d'occupation de lit à l'USI utilisées en une journée divisé par le nombre total d'heures d'occupation de lit à l'USI disponibles pour ladite journée. Nous avons créé des modèles de régression logistique à effets mixtes contrôlant les covariables pertinentes afin d'évaluer l'impact des quintiles d'occupation à l'admission sur la mortalité hospitalière totale (USI et étages) et précoce (72 h) à l'USI.*

Résultats *Cette analyse a inclus 10 365 admissions à l'USI pour 8562 différents patients. Par rapport aux admissions à l'USI dans le quintile d'occupation médian, les admissions ayant eu lieu dans le quintile le plus élevé et le suivant ont été associées à une augmentation significative de la probabilité de mortalité hospitalière (1^er^ quintile : rapport de cotes [RC], 1,33; intervalle de confiance [IC] 95 %, 1,12 à 1,59; valeur P < 0,001; 2^e^ quintile : RC, 1,21; IC 95 %, 1,02 à 1,44; valeur P < 0,03). Aucune association n'a été observée entre le taux d'occupation à l'admission et la mortalité dans les premières 72 h dans l'USI.*

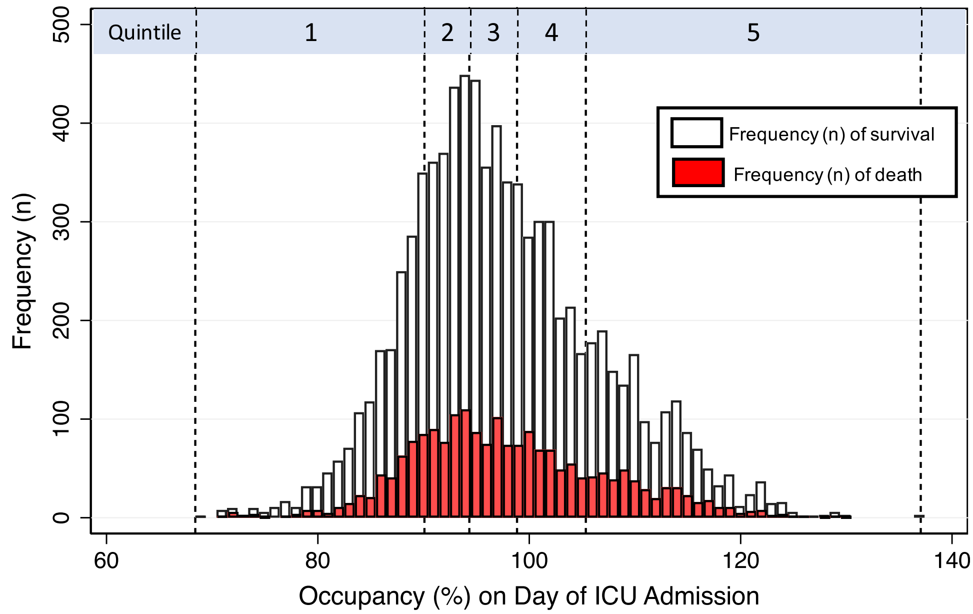
Conclusion *L'admission à l'USI lors d'un jour de forte occupation a été associée à une augmentation de la mortalité hospitalière, mais pas à une augmentation de la mortalité à l'USI dans les premières 72 h. Les pressions sur la capacité de l'USI pourraient engendrer d'importantes conséquences négatives pour les patients, mais des recherches supplémentaires sont nécessaires afin de bien cerner les effets complexes de ces pressions.*

Outcomes of critically ill patients are broadly dependent on three general factors: 1) inherent patient characteristics (age, sex, acuity, etc.), 2) the specific therapies and interventions delivered for care (medications, mechanical ventilation, etc.), and 3) process-of-care factors (unit strain, triage, delayed admission, worker fatigue, etc.). Process-of-care factors describe the larger organizational structure and environment to which a patient is admitted.

Of these process-of-care factors, there is growing interest in assessing the impact of intensive care unit (ICU) capacity strain on patient outcomes. Intensive care unit capacity strain can be defined as the discrepancy between available ICU resources (beds, staff, equipment, etc.) and the current demand to admit patients in need of critical care.[1,2] Several metrics of capacity strain exist, with the most widely used being occupancy of the ICU. The metric of occupancy, in this context, is a proxy for the amount of patient workload the ICU is experiencing. Although occupancy as a proxy for workload is unable to capture specific patient complexity and workload intensity, in general as occupancy increases so does the demand on ICU physicians and staff. Most definitions of occupancy involve the daily ICU census. Yet, a more appropriate method of measuring capacity strain is determining ICU occupancy as the fraction of available bed hours utilized to provide patient care (patient bed hours divided by total available bed hours).[3] This definition more accurately characterizes the workload burden on the ICU by calculating occupancy using the exact number of hours ICU beds were occupied divided by the total amount of funded hours available at a given time.

There is conflicting evidence evaluating the association between ICU occupancy and mortality. A large observational study by Iwashyna *et al.* examining 200,499 patients in 108 ICUs did not show an association between ICU occupancy and inpatient mortality.[4] They defined ICU occupancy as the daily census divided by the mean census for the entire study period. More recently, an analysis by Gabler *et al.* of 264,401 patients admitted to 155 ICUs found an association between higher ICU census and mortality.[5] In that study, ICU occupancy was defined as the daily census compared with yearly mean census standardized for ICU capacity. Both studies are limited by their use of the ICU census to measure occupancy, which may be less precise. In addition, prior studies have used aggregate data to determine ICU occupancy and overall capacity strain—not individual patient data.[6,7] Aggregating by time period (months, years) may bias the association between ICU occupancy and outcome as granular variation in occupancy gets lost and seasonal trend may be picked up instead. Furthermore, a systematic review on indicators for ICU capacity strain highlighted the uncertainty of current evidence, the lack of consistent definitions for several

Fig. 1 Histogram of total inpatient death by intensive care unit (ICU) admission occupancy quintiles



Quintile	1	2	3	4	5
Pr(Prob)	19%	19%	18%	21%	21%
OR[a]	1.08	1.08	1.00	1.19	1.24
95% CI	0.92-1.26	0.93-1.27	-	1.02-1.39	1.07-1.45
P-value	0.33	0.31	-	0.03	0.006

Abbreviations: Pr(Prob) = Predicted probabilities, OR =odds ratio, CI= confidence interval
[a] Unadjusted odds ratio for inpatient mortality

indicators, and a need to evaluate multiple indicators concurrently.[1]

For these reasons, we sought to conduct a single-centre retrospective cohort study using granular, individual admission-level data to characterize the relationship between ICU occupancy at the time of admission and inpatient mortality. Concurrently, we also evaluated several metrics related to the process of ICU admission (delay to admission, number of additional same day admissions, afterhours and weekend admission) and their impact on mortality.

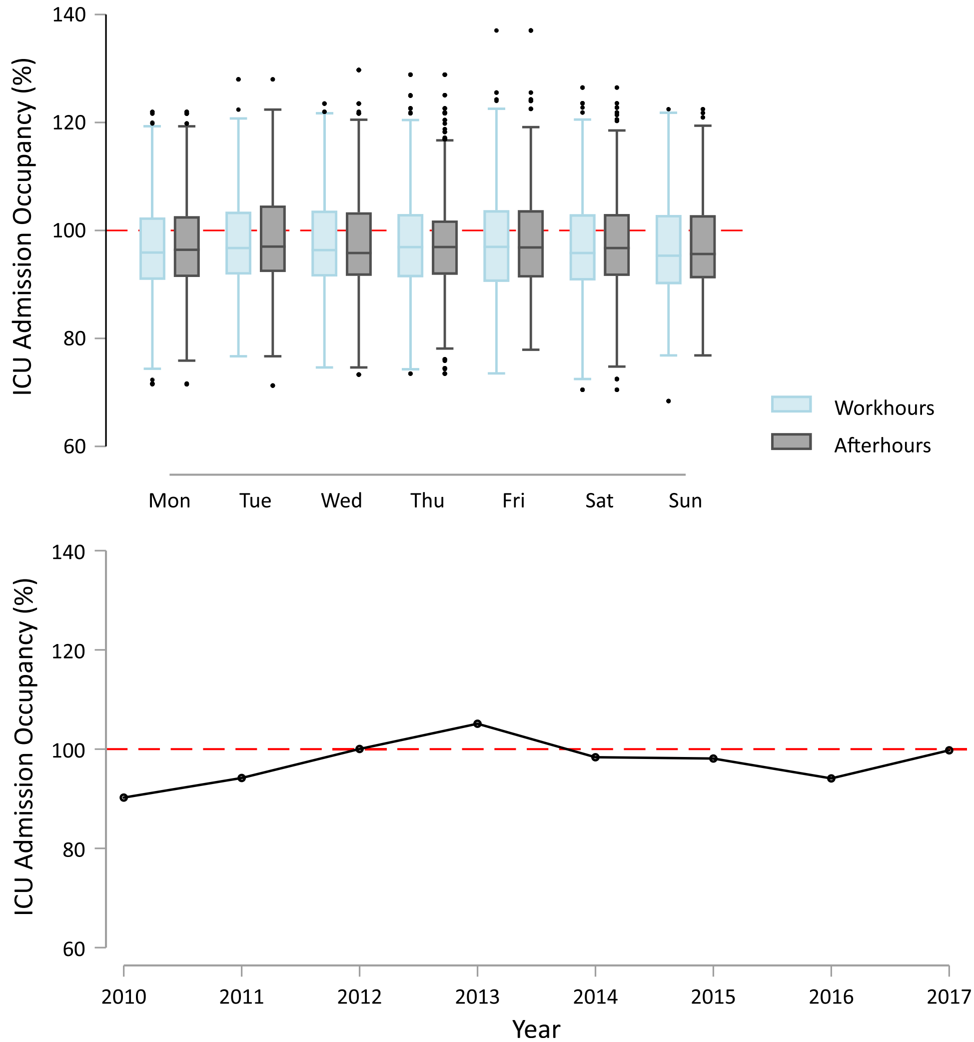
Methods

Study design and setting

We conducted a retrospective cohort study of all patients admitted to the ICU at Vancouver General Hospital (VGH) between 1 April 2010 and 10 August 2017. We report these results in accordance with the Strengthening the Reporting of Observational Epidemiology statement.[8] The ICU at VGH is a closed, 32-bed mixed medical surgical unit affiliated with the University of British Columbia. The ICU had an average 1,402 admissions per year during the study period. Yearly admissions increased at several points during the study period as the number of ICU beds increased from 27 to 29 in 2013, and then from 29 to 32 in 2015. Our ICU averages 3.6 admissions per day and that number is also trending upwards as new ICU beds are added.

Although there are 32 physical beds, the ICU operates as an overflow unit. Patients physically outside of the ICU can be attended by the ICU care team when beds are not available (thereby allowing patients to be admitted to the ICU without being physically present in the ICU). For example, when a patient is admitted to the ICU from the postanesthesia recovery room (PAR) they may need to stay in the PAR until there is enough room in the ICU. They are still under ICU care even though they are not physically in the ICU. If they are deemed to be very ill, they would be physically moved to the ICU and another patient in the ICU would be overflowed back to the PAR. Of note, there is also a 12-bed high-acuity unit at our centre, which is not included in this analysis. All elective surgeries are admitted to the high-acuity unit and not the main ICU. The main ICU only admits emergency patients, so our analysis only includes emergency ICU admissions. Care is provided by three ICU teams and each team consists of an attending physician, a critical care medicine fellow, several resident

Fig. 2 Intensive care unit (ICU) occupancy by admission time, day of week, and year



physicians and other clinical associates (nurses, respiration therapists, pharmacists). These teams rotate through being on-call overnight during a one-week period. The ICU operates on an approximately 1.2:1 nurse to patient ratio. Overnight, there are two to three senior (second or third post-graduate year) resident physicians along with either a clinical associate or critical care fellow in attendance. The ICU attending takes calls from home but is expected to be at the bedside within 15 min. New patients are typically assigned to the team that is on-call on the day of admission, although patients can be redistributed across teams during overloaded periods.

Data

Data were obtained from the British Columbia (BC) Critical Care Database, which records patient-specific data for all patients admitted to the ICU.[9] This database records baseline demographics (age, sex), diagnostics (primary diagnosis), illness acuity, laboratory tests, and device information (mechanical ventilation, vasoactive medication) along with processual factors such as dates, times, and source of any admission, transfer, or discharge. Severity of illness is characterized by the Acute Physiology And Chronic Health Evaluation (APACHE) II score and is performed within the first 24 hr of an ICU stay.[10] The APACHE II score can range from 0 to 71 and a higher score indicates more severe disease and consequently a higher risk of mortality. This ICU patient database also contains daily information related to patient occupancy—number of patients admitted, hours of patient care performed, and number of available beds. To address substantial missingness ($> 1\%$) we conducted a multiple imputation analysis. The only variable we expected to contain substantial missingness was the APACHE II score since the scores are determined at the end of the first day of admission to the ICU. If a patient was deceased or discharged on the same day of admission, they would not have an APACHE II score. The primary diagnosis category contained insignificant missing data ($< 1\%$) and admissions missing this variable were excluded from the analysis. No other baseline variables outcomes possessed missing data. There were no missing values for neither our primary and secondary exposures nor our primary and secondary outcomes.

Exposure

By linking each ICU admission to daily ICU characteristics, we were able to identify several indicators of capacity strain for each individual ICU admission. Our principal exposure was ICU occupancy on the calendar day of admission, defined as the number of bed hours utilized in a day divided by the total amount of funded bed hours available for that day (number of funded beds x 24 hr). Compared with other measures of occupancy, this method is considered to be a better representation of the actual ICU workload.[3] In the analysis, we discretized ICU admission occupancy into quintiles. Additional exposures of ICU capacity strain included the total number of admitted patients on the focal patient's day of admission (excluding the focal patient), and whether the focal patient's admission was delayed. We denoted an admission as delayed with a binary variable if the following two time stamps were not exactly matching: 1) when the patient was evaluated by the ICU team and recommended for ICU admission, and 2) when the patient was admitted to ICU care. Additional strain exposures included temporal factors of admission such as overnight (between 7:00 pm and 6:59 am), weekend (Saturday–Sunday), and season (winter [December–February], spring [March–May], summer [June–August], fall [September–November]).

Outcomes

Outcomes of interest included total inpatient mortality and ICU mortality within 72 hr. Total inpatient mortality included any death that occurred in the ICU or in the hospital after ICU discharge.

Statistical methods

Data were first explored qualitatively to ensure all variables were cohesive and logical. The base unit of analysis was ICU admission so we treated the data as longitudinal and controlled for repeatedly admitted patients. Our sample size was based on convenience, knowing that during the seven-year study period we would definitively have an adequate number of events (inpatient mortality) per covariate to build a robust multivariable model. Our primary exposure variable was ICU occupancy on the day of admission. Our cohort was then divided into five equal quintiles ordered by ascending ICU admission occupancy percentage. Quintile 1 was defined as the lowest and quintile 5 as the highest with respect to ICU admission occupancy. Quintiles were compared with the median (quintile 3). Descriptive statistics (Table 1) are presented for each occupancy quintile. All continuous variables were presented as mean (standard deviation [SD]) unless stated otherwise and categorical variables were presented as total number (%).

Multiple imputations were performed for 1,167 missing APACHE II scores using the *mi impute* and *mi estimate* commands in STATA statistical software (StataCorp. 2017. Stata Statistical Software: Release 15, College Station, TX, USA: StataCorp LLC). The imputation used simple linear regression for a continuous variable (APACHE II), but it was truncated between 0 and 71 to accurately represent the theoretical range of APACHE II scores. Twenty iterations of imputation were performed and the imputed APACHE II values were assessed for coherence.

We constructed two logistic regression models to evaluate the association between ICU admission occupancy and both inpatient mortality and 72-hr ICU mortality. As patients could be admitted more than once, we accounted for within-patient correlation using a mixed-effects logistic regression model with the random-effect specified at the patient level (STATA command *xtreg*). Each model controlled for important baseline covariates such age, sex, APACHE II score, the admitted year, primary diagnosis category, and several others marked as indicator variables including ICU admission source (emergency room *vs* operating room *vs* postanesthesia recovery room *vs* hospital floor ward *vs* other [e.g., direct admission from another institution]), mechanical ventilation use (yes or no), and vasopressor use (yes or no). The aforementioned additional indicators of capacity strain were also included in the model (overnight admission, weekend admission, admission season) along with the total number of additional admissions on that day (not including the focal admission), and delay to admission. To test linearity, likelihood-ratio tests were used to compare continuous ICU admission occupancy with the ordinal quintiles. Results of the logistic regression models were displayed as odd ratios (OR) with 95% confidence intervals (CI).

Several sensitivity analyses were performed to assess the robustness of the models. We evaluated the potential interaction between admission timing (weekend *vs* weekday and afterhours *vs* workhours) and did not find any significant modification. We also conducted a complete case analysis (without any imputed APACHE II scores). All analyses were performed using STATA.

Results

Descriptive statistics

A total of 10,396 ICU admissions of 8,593 patients occurred at VGH between 1 April 2010 and 10 August 2017. Thirty-one (1%) of the 10,396 admissions were missing a primary disease classification and were excluded from our analysis resulting in 10,365 ICU admissions and 8,562 unique patients being included in the final analysis. Overall, 2,022 inpatient deaths and 723 early ICU deaths occurred out of 10,365 admissions, leading to an inpatient mortality rate of 19.5% and a 72-hr ICU mortality rate of 7.0%. Descriptive statistics (Table 1) are presented for each occupancy quintile. The range of occupancy percentages associated with each quintile are 68–89% (quintile 1), 90–94% (quintile 2), 95–99% (quintile 3), 100–105% (quintile 4), and 106–137% (quintile 5).[A] Mean (SD) APACHE II scores for occupancy quintiles 1 through 5 were 18.8 (7.0), 18.6 (6.8), 18.7 (7.0), 18.6 (7.0), and 18.3 (6.9) respectively.

Association between admission occupancy and mortality

Unadjusted inpatient mortality for each admission occupancy quintile is presented in Fig. 1. Admission in the highest occupancy quintile (quintile 5) and second highest occupancy quintile (quintile 4) is associated with a significant increase in the odds of inpatient mortality when compared with the median occupancy quintile (quintile 3). The frequencies of ICU admission survival *vs* ICU admission death are presented as histograms showing their distributions across ICU occupancy on the day of admission (Fig. 1).

The results of the multivariable analysis are presented in Table 2. On adjusted analysis, admission to the ICU when occupancy was in the top quintile (above 105%) was associated with a significant increase in the odds of inpatient mortality (OR, 1.33; 95% CI, 1.11 to 1.59) compared with the median quintile (between 94% and 99%). A significant increase in the odds of inpatient mortality was also seen with admission to the ICU when occupancy was in the second highest quintile (between 100% and 105%) compared with the median quintile (between 94% and 99%) (OR, 1.21; 95% CI, 1.02 to 1.44). Whereas, in the two lowest quintiles, the odds of inpatient mortality were not statistically different from the median quintile (OR, 1.09; 95% CI, 0.91 to 1.30; OR, 1.10; 95% CI, 0.93 to 1.31). On the outcome of early ICU death (within 72 hr), there were no significant differences in ICU admission occupancy.

[A] The patients can be admitted to the ICU without being physically present inside the ICU and occupying a bed.

Association between other admission process factors and mortality

We assessed the impact of several other indicators of capacity strain on ICU mortality in the logistic regression model concurrently with the primary strain indicator, ICU occupancy (Table 2). Neither total inpatient mortality nor 72-hr ICU mortality were associated with factors surrounding the ICU admission process such as delay to ICU admission and number of additional admissions on the day of focal patient's admission. Similarly, neither total inpatient mortality nor early ICU mortality was associated with factors related to the timing of ICU admission such as afterhours admission (between 7 pm and 6:59 am), weekend admission (Saturday or Sunday) or season of ICU admission (winter, spring, summer, fall). Temporal trends such as afterhours admission, weekend admission, and year were not significantly associated with changes in occupancy percentage (Fig. 2).

Sensitivity analyses

Several sensitivity analyses were performed to test the robustness of the presented results. A complete case analysis excluding all admissions without APACHE II scores was also conducted. Results matched those of our primary analysis using multiple imputed values for missing APACHE II scores (see eTable, available as Electronic Supplementary Material).

Discussion

Our single-centre retrospective cohort study showed a significant increase in the odds of inpatient mortality among patients admitted to the ICU when ICU occupancy was in the highest and second highest quintile versus the median quintile. Nevertheless, no significant association was observed between ICU admission occupancy and early (within 72 hr) ICU mortality. No other metrics of ICU capacity strain had a significant impact on either inpatient or early ICU mortality.

The current state of the literature shows conflicting evidence on the impact of ICU occupancy on mortality. This conflict is likely explained to some degree by the varying definitions of occupancy and the complex processual nature of the setting. Furthermore, in contrast to our current study, the available literature typically uses definitions of capacity that collapse unit occupancy over time, thereby subjecting their results to aggregation bias. In

Table 1 Demographics and descriptive statistics

		Overall	Occupancy quintile 1 (*Lowest*)	Occupancy quintile 1	Occupancy quintile 1 (*Median*)	Occupancy quintile 1	Occupancy quintile 1 (*Highest*)	P value
Total admission		10,365	2,074	2,073	2,073	2,073	2,072	
Unique patients		8,562	1,744	1,745	1,717	1,682	1,674	
Age		57.9 (17.3)	57.5 (17.2)	57.8 (17.4)	58.2 (17.2)	58.1 (17.3)	57.9 (17.5)	0.74
Female		3,749 (36.2%)	762 (36.7%)	715 (34.5%)	750 (36.2%)	757 (36.5%)	765 (36.9%)	0.49
APACHE II score								
	0–5	135 (1.3%)	21 (1.0%)	27 (1.3%)	29 (1.4%)	32 (1.5%)	26 (1.3%)	0.001
	6–10	919 (8.9%)	182 (8.8%)	179 (8.6%)	180 (8.7%)	180 (8.7%)	198 (9.6%)	
	11–15	2,175 (21.0%)	462 (22.3%)	427 (20.6%)	421 (20.3%)	446 (21.5%)	419 (20.2%)	
	16–20	2,549 (24.6%)	515 (24.8%)	505 (24.4%)	519 (25.0%)	496 (23.9%)	514 (24.8%)	
	21–25	1,961 (18.9%)	406 (19.6%)	436 (21.0%)	406 (19.6%)	354 (17.1%)	359 (17.3%)	
	26–30	949 (9.2%)	198 (9.5%)	167 (8.1%)	199 (9.6%)	207 (10.0%)	178 (8.6%)	
	30+	510 (4.9%)	110 (5.3%)	97 (4.7%)	106 (5.1%)	107 (5.2%)	90 (4.3%)	
	Missing	1,167 (11.3%)	180 (8.7%)	235 (11.3%)	213 (10.3%)	251 (12.1%)	288 (13.9%)	
Source of ICU admission								
Emergency room		3,338 (32.2%)	658 (31.7%)	642 (31.0%)	691 (33.3%)	653 (31.5%)	694 (33.5%)	<0.001
Operating room†		1,951 (18.8%)	400 (19.3%)	425 (20.5%)	366 (17.7%)	384 (18.5%)	376 (18.1%)	
Postanesthesia recovery room		850 (8.2%)	127 (6.1%)	162 (7.8%)	167 (8.1%)	173 (8.3%)	221 (10.7%)	
Hospital ward floor		2,506 (24.2%)	473 (22.8%)	478 (23.1%)	535 (25.8%)	521 (25.1%)	499 (24.1%)	
Other		1,720 (16.6%)	416 (20.1%)	366 (17.7%)	314 (15.1%)	342 (16.5%)	282 (13.6%)	
Primary diagnosis category								
Shock (cardiac/septic)		1,703 (16.4%)	299 (14.4%)	330 (15.9%)	330 (15.9%)	391 (18.9%)	353 (17.0%)	0.05
Musculoskeletal/dermatologic		122 (1.2%)	28 (1.4%)	23 (1.1%)	21 (1.0%)	26 (1.3%)	24 (1.2%)	
Metabolic/toxicity		412 (4.0%)	94 (4.5%)	90 (4.3%)	78 (3.8%)	74 (3.6%)	76 (3.7%)	
Gastrointestinal/urologic		1,508 (14.5%)	308 (14.9%)	328 (15.8%)	309 (14.9%)	266 (12.8%)	297 (14.3%)	
Hematologic		770 (7.4%)	153 (7.4%)	169 (8.2%)	154 (7.4%)	160 (7.7%)	134 (6.5%)	

Table 1 continued

	Overall	Occupancy quintile 1 *(Lowest)*	Occupancy quintile 1	Occupancy quintile 1 *(Median)*	Occupancy quintile 1	Occupancy quintile 1 *(Highest)*	P value
Neurologic	2,808 (27.1%)	557 (26.9%)	550 (26.5%)	543 (26.2%)	575 (27.7%)	583 (28.1%)	
Respiratory/pneumonia	3,042 (29.3%)	635 (30.6%)	583 (28.1%)	638 (30.8%)	581 (28.0%)	605 (29.2%)	
Mechanical ventilation	9,080 (87.6%)	1,775 (85.6%)	1,791 (86.4%)	1,816 (87.6%)	1,830 (88.3%)	1,868 (90.2%)	<0.001
Vasopressor use	7,118 (68.7%)	1,412 (68.1%)	1,412 (68.1%)	1,400 (67.5%)	1,467 (70.8%)	1,427 (68.9%)	0.19
Afterhours ICU admission *(7 pm to 6:59 am)*	5,048 (48.7%)	966 (46.6%)	1,007 (48.6%)	1,046 (50.5%)	1,000 (48.2%)	1,029 (49.7%)	0.12
Weekend ICU admission *(Saturday / Sunday)*	2,947 (28.4%)	667 (32.2%)	567 (27.4%)	546 (26.3%)	599 (28.9%)	568 (27.4%)	<0.001
Season of ICU admission							
Winter	2,455 (23.7%)	276 (13.3%)	415 (20.0%)	581 (28.0%)	651 (31.4%)	532 (25.7%)	<0.001
Spring	2,727 (26.3%)	419 (20.2%)	567 (27.4%)	657 (31.7%)	556 (26.8%)	528 (25.5%)	
Summer	2,767 (26.7%)	875 (42.2%)	644 (31.1%)	438 (21.1%)	360 (17.4%)	450 (21.7%)	
Fall	2,416 (23.3%)	504 (24.3%)	447 (21.6%)	397 (19.2%)	506 (24.4%)	562 (27.1%)	
Delayed ICU admission	1,420 (13.7%)	128 (6.2%)	174 (8.4%)	285 (13.7%)	382 (18.4%)	451 (21.8%)	<0.001
Number of admissions on Day of ICU admissionc	3 (2-5)	3 (2-4)	3 (2-4)	3 (2-5)	4 (2-5)	3 (2-4)	<0.001

APACHE = Acute Physiology And Chronic Health Evaluation; ICU = intensive care unit. Continuous variables are mean (standard deviation) while categorical variables are number (percentage) unless otherwise specified.

* Significance tests were analysis of variance, Pearson's Chi squared, and Kruskal–Wallis when appropriate.

† All operating room admissions are emergency admissions. Admissions post-elective procedures are admitted to a separate high-acuity unit, which is not included in this analysis.

‡ Median [interquartile range].

Table 2 Logistic regression models for total inpatient (ICU and hospital) and early ICU mortality

Predictor	Inpatient mortality OR	95% CI	*P* value	Early ICU mortality OR	95% CI	*P* value
Occupancy on day of ICU admission						
(Divided into quintiles)						
1 *(lowest)*	1.09	0.91 to 1.30	0.34	0.95	0.67 to 1.35	0.77
2	1.10	0.93 to 1.31	0.27	1.04	0.75 to 1.45	0.81
3 *(median)*	1.00	-	-	1.00	-	-
4	1.21	1.02 to 1.44	0.03	1.19	0.85 to 1.66	0.31
5 *(highest)*	1.33	1.12 to 1.59	0.001	1.16	0.82 to 1.64	0.41
Age	1.02	1.01 to 1.02	<0.001	1.02	1.01 to 1.02	<0.001
Female sex	1.14	1.02 to 1.27	0.02	1.43	1.14 to 1.80	0.002
APACHE II score admission	1.07	1.06 to 1.09	<0.001	1.09	1.06 to 1.11	<0.001
Year						
2010	1.00	-	-	1.00	-	-
2011	0.96	0.76 to 1.20	0.71	1.03	0.66 to 1.61	0.90
2012	0.90	0.70 to 1.13	0.35	0.87	0.55 to 1.39	0.57
2013	0.85	0.67 to 1.09	0.20	0.70	0.43 to 1.15	0.16
2014	0.78	0.62 to 0.98	0.04	0.66	0.41 to 1.05	0.08
2015	0.67	0.53 to 0.85	0.001	0.63	0.40 to 1.01	0.05
2016	0.76	0.60 to 0.95	0.02	0.71	0.45 to 1.13	0.13
2017	0.89	0.68 to 1.15	0.37	0.73	0.43 to 1.23	0.24
Source of ICU admission						
Emergency room	1.00	-	-	1.00	-	-
Operating room*	0.56	0.47 to 0.67	<0.001	0.35	0.23 to 0.52	<0.001
Postanesthesia recovery room	0.52	0.41 to 0.66	<0.001	0.25	0.14 to 0.45	<0.001
Hospital ward floor	1.20	1.03 to 1.40	0.02	0.60	0.45 to 0.81	0.001
Other	1.19	1.01 to 1.40	0.04	0.72	0.53 to 0.99	0.04
Primary diagnosis category						
Shock (septic or cardiac)	1.00	-	-	1.00	-	-
Musculoskeletal/dermatologic	0.43	0.23 to 0.82	0.01	0.16	0.04 to 0.67	0.01
Metabolic/toxicity	0.32	0.21 to 0.47	<0.001	0.13	0.06 to 0.30	<0.001
Gastrointestinal/urologic	0.52	0.43 to 0.64	<0.001	0.19	0.11 to 0.31	<0.001
Hematologic	0.56	0.45 to 0.70	<0.001	0.25	0.15 to 0.40	<0.001
Neurologic	1.14	0.97 to 1.35	0.11	0.78	0.58 to 1.06	0.12
Pulmonary/pneumonia	0.47	0.40 to 0.55	<0.001	0.15	0.10 to 0.24	<0.001
Mechanical ventilation	1.99	1.61 to 2.46	<0.001	2.37	1.53 to 3.70	<0.001
Vasopressor use	2.05	1.77 to 2.38	<0.001	1.78	1.32 to 2.39	<0.000
Afterhours ICU admission *(7 pm to 6:59 am)*	1.08	0.97 to 1.21	0.15	1.08	0.87 to 1.33	0.47
Weekend ICU admission *(Saturday/Sunday)*	0.98	0.87 to 1.10	0.74	0.95	0.76 to 1.20	0.70
Season of ICU admission						
Winter	1.00	-	-	1.00	-	-
Spring	0.98	0.84 to 1.14	0.81	0.92	0.69 to 1.25	0.61
Summer	1.04	0.89 to 1.21	0.63	1.00	0.74 to 1.36	0.99
Fall	1.07	0.91 to 1.25	0.41	1.06	0.78 to 1.44	0.73
Delay to ICU admission	0.96	0.80 to 1.15	0.65	0.76	0.53 to 1.07	0.12
Additional ICU admissions on day of admission	0.99	0.96 to 1.02	0.67	0.97	0.91 to 1.03	0.35

APACHE = Acute Physiology And Chronic Health Evaluation; CI= confidence interval, ICU = intensive care unit, OR = odds ratio. *All operating room admissions are emergency admissions. Admissions post-elective procedures are admitted to a separate high-acuity unit, which is not included in this analysis.

2004, Iapichino *et al.* conducted a prospective, multicentre cohort study of 12,615 patients from 89 ICUs across Europe.[6] Although their main research question involved the impact of high volume versus low volume centres, they found that an occupancy rate above 80% (*vs* < 80%) was associated with a significantly greater odds of mortality (OR, 1.35; 95% CI, 1.16 to 1.56).[6] In this study, occupancy was defined as the ratio of possible nursing days in the ICU to the total number of patient days. They hypothesized that the increase in overall mortality may be due to staff overwork and the potential for increased medical errors. More recently, an analysis by Gabler et. al. of 264,401 patients admitted to 155 ICUs found a significant association between ICU census on the day of admission and post-ICU inpatient mortality (OR, 1.02; 95% CI, 1.00 to 1.03).[5] In this study, ICU occupancy was defined as the daily census compared with annual mean census standardized for centre size.[5]

In contrast to the above results, a large observational study by Iwashyna *et al.* examining 200,499 patients in 108 ICUs did not identify any association between ICU occupancy and inpatient mortality.[4] They defined ICU occupancy as the daily census divided by the mean census for the entire study period. These standardized occupancy values were then divided into deciles and ICU admissions in the highest deciles and lowest deciles were compared with those that occurred in the median decile. They note that ICUs included in their study were able to scale up their operations to meet demands of increased occupancy without negative effects to clinical outcomes. Nevertheless, the authors did mention that individual practitioners may suffer directly from the increased workload seen during periods of high occupancy.[4,11–14] A literature review of optimal occupancy in the ICU further emphasizes the lack of a consistent definition of occupancy and the significant limitations of past studies assessing occupancy in the ICU.[3] They recommend that occupancy be calculated as the total number of patient bed hours divided by the total number of available bed hours, as this definition more precisely estimates the patient workload.[3] We were able to utilize this definition of occupancy given the granularity of our data.

Occupancy is a metric of capacity strain in the ICU. Capacity strain is the discrepancy between the resources available in the ICU (beds, staffing, equipment) and the current demand to admit patients in need of critical care.[1,2] A recent systematic review identified 16 different indicators of capacity strain and highlighted the need to further research the implications of these indicators.[1] The measures used in this analysis stem from the overarching concept of capacity strain and have been independently associated with ICU staff perceptions of workload.[5,15] Our analysis focuses specifically on capacity strain at the time of admission to the ICU and our primary exposure was ICU occupancy on the day of admission (divided into quintiles). In addition, we assessed other capacity strain factors such as delayed admission and the number of additional admissions on the same day of the focal admission. An exclusive analysis of sepsis patients admitted to the ICU revealed a significant association between increasing admission occupancy and odds of inpatient mortality, but this association was not observed for other capacity strain metrics such as delayed admission and the number of additional admissions on the day of admission.[16] Our results appear to be similar as, in contrast to our primary results, other potential metrics of capacity strain surrounding admission, such as delay to admission and number of additional admissions on the same day did not have any impact on mortality. Although speculative, these results could be explained by confounding by severity, whereby clinicians selectively admit more severely ill patients to the ICU and allow those who are less severely ill to remain outside of the ICU. Additionally, it is plausible that ICU occupancy captured higher level system-wide strain on the ICU that was not directly captured by these other potential metrics of capacity strain. We also evaluated the potential interactions that the timing of admission (afterhours *vs* workhours, weekend *vs* weekday, and season) may have had on our results, although we did not find any independent effects or interactions of these variables. A recent Canadian analysis did find that afterhours admission was associated with an increase in early ICU mortality but only when occupancy was above 90%.[17] Our findings did not replicate these results. Overall, of the processual factors assessed in this analysis, ICU occupancy appeared to be the dominating factor that impacts mortality. These results highlight the significant implications ICU occupancy has for ICU operations over other processual metrics. We believe these results emphasize that in a large tertiary-centre ICU with built-in flexibility, high occupancy and capacity strain may have significant clinical consequences for patients. The solution to this problem is not an easy one to decipher, but it may simply start with a broader acknowledgment and awareness of the issue. It has been shown that clinicians certainly perceive the effects of capacity strain,[4,11–14] but the acknowledgment that strain may have significant attributable risks and clinical consequences for patients may be lacking. We do not believe that the solution solely lies in increasing funding and the number of total available beds as simply expanding capacity is often not feasible because of space limitations, staffing shortages, and government regulations.[18] Additionally, it has been shown that in a setting of an ICU operating near or at capacity, an increase in funding leads to higher fixed costs and long-term inefficiencies.[18] Thus, part of the solution may lie in increased flexibility and efficiency. Although speculative, the formation of "flex" critical care or high-acuity beds that operate at times of high occupancy may offer some of this flexibility. It may be that operating below rather than at capacity is a more efficient and effective way to operate an ICU, and deserves inquiry. Overall, we hope that our study increases awareness at other centres and triggers the development of local strategies to mitigate the potential negative clinical consequences of capacity strain.

In contrast to the results for inpatient mortality, our secondary outcome measure of early (72 hr) ICU mortality was not associated with ICU admission occupancy. It may be that early ICU death is more dependent on patient characteristics than process-of-care factors. In an analysis of sepsis patients admitted to the ICU, occupancy was associated with mortality but this effect waned in severe sepsis patients.[16] Additionally, in a study of patients with rapid clinical deterioration, the lack of ICU beds was not associated with higher mortality.[19] Finally, there may also have been insufficient events of early ICU mortality to discern any potential effects of occupancy.

There are several limitations to this study that should be noted. Firstly, our study only included one large quaternary centre and our results may not be generalizable to other centres. Our large (32 bed) ICU routinely operates near capacity and often overflows patients to other wards when capacity is reached. As this study shows, our centre often operates above the funded capacity. These unique processual characteristics should be noted when generalizing study results. Nevertheless, a recent analysis of a smaller centre in a resource-limited setting produced similar results to our study.[20] Another limitation that should be noted is, despite our granular patient-level data, we did not possess data on the exact bed availability at the time of patient admission, which is a potentially useful metric of patient flow. Despite our more precise calculation of occupancy using patient hours, it is still an aggregated value over the course of a calendar day and not the instantaneous occupancy at the exact time a patient is admitted to the ICU. Additionally, this study is retrospective and observational in nature and despite multivariable adjustment, there is most certainly unmeasured and residual confounding. Another limitation is the appreciable (11.5%) and non-random missing APACHE II values. Nevertheless, the missing values were rigorously imputed using a data set rich in patient-level variables and the conclusion of the logistic regression was consistent between the multiple imputations and the complete case analysis. Lastly, the focus of this analysis was limited to capacity strain at the time of admission and subsequent outcomes. Future research assessing the impact of capacity strain throughout the ICU stay and at discharge is warranted.

Conclusion

In our single-centre retrospective analysis, admissions to the ICU on days when occupancy was high were associated with increased odds of inpatient mortality. Compared with admissions in the median occupancy quintile, admissions in the two top occupancy quintiles had a statistically significant 33% (quintile 5) and 21% (quintile 4) increase in the odds of inpatient mortality. No other indicator of capacity strain was associated with neither inpatient nor early ICU mortality. This analysis explored multiple processual factors surrounding ICU admission and found that ICU occupancy at the time of ICU admission is the dominating processual factor that impacts mortality. This result sheds light on the importance of ICU occupancy in managing ICU operations over other capacity strain metrics. Nevertheless, future research is needed to characterize the impact of capacity strain throughout the process of ICU admission, stay, and discharge. Capacity strain, particularly high occupancy, may have significant clinical consequences in addition to major implications for ICU staff and managers.

Competing interests The authors declare that they have no competing interests.

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Author contributions *Nicholas A. Fergusson* and *Donald E. G. Griesdale* conceived and designed the overarching framework for the project. *Nicholas A. Fergusson* performed data retrieval, cleaning, and statistical analyses with the assistance and guidance of *Steve Ahkioon* and *Donald E. G. Griesdale. Mahesh Nagarajan*, *Vinay K. Dhingra*, *Yichuan Ding*, *Eric Park*, *Najib Ayas*, and *Dean R. Chittock* provided guidance and logistical feedback. All authors contributed to and critically reviewed the final version of this manuscript.

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