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Near-simultaneous intensive care unit (ICU) admissions and all-cause mortality: a cohort study

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Abstract

Purpose: Prior studies have reported the adverse effects of strain on patient outcomes. There is a paucity of literature about a type of strain that may be caused by near-simultaneous intensive care unit (ICU) admissions. We hypothesized that when multiple admissions arrive nearly at the same time, the ICU teams are excessively strained, and this leads to unfavorable patient outcomes.

Methods: This is a retrospective cohort study of consecutive adult patients admitted to an academic medical ICU of a tertiary referral center over five consecutive years. Primary outcomes were the all-cause hospital and ICU mortality.

Results: We enrolled 13,234 consecutive ICU admissions during the study period. One-fourth of the admissions had an elapsed time since the last admission (ETLA) of < 55 min. Near-simultaneous admissions (NSA) had on average, a higher unadjusted odds ratio (OR) of ICU death of 1.16 (95% CI 1–1.35, $P = 0.05$), adjusted 1.23 (95% CI 1.04–1.44, $P = 0.01$), unadjusted hospital death of 1.11 (95% CI 0.99–1.24, $P = 0.06$), adjusted 1.20 (95% 1.05–1.35, $P = 0.004$), and a lower adjusted OR of home discharge of 0.91 (95% CI 0.84–0.99, $P = 0.04$). NSA was associated with 0.16 (95% CI 0.04–0.29, $P = 0.01$) added days in the ICU. For each incremental unit increase of the logarithmic transformation of ETLA [log (ETLA in minutes)], the average adjusted hospital mortality OR incrementally decreased by an added average OR of 0.93 (95% CI 0.89–0.97, $P = 0.001$).

Conclusion: Our results suggest that near-simultaneous ICU admissions (NSA) are frequent and are associated with a dose-dependent effect on mortality, length of stay, and odds of home versus nursing facility discharge.

Keywords: Time-pressure, Mortality, Strain, Workload

Introduction

As critical care utilization continues to rise in the United States [1], some intensive care units (ICUs) experience scenarios where transient spikes exceed the available capacity. These busy ICUs increasingly face more resource strain [2]. One scenario of resource strain is when critically ill patients arrive in the ICU nearly at the same time [3], i.e. during near-simultaneous admissions [4]. These situations exert time-pressure and obligate caretakers to ration between various tasks that cannot be accomplished simultaneously. This phenomenon has been described as triage [5], a form of rationing [3, 6–9]. During these occurrences of *time-pressure* and extraordinary clinical, procedural and communication demands, critical care teams overextend with

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multitasking and are called to prioritize one patient's emergent, life-threatening needs over the others' and vice versa. To this day, there is no consistent method, or protocol, and limited literature to guide how critical care teams should approach this type of strain. Studies have shown a lack of concordance between institutions and intensivists regarding the triage of the critically ill during these periods of high demand, signifying a high degree of subjectivity and process variability [10]. Some studies have suggested a correlation of a similar type of strain, capacity strain, with worse outcomes. The capacity strain describes the ability of the ICU to "accommodate patients in greater numbers and rising acuity [11]" which, in turn, leads to adverse patient outcomes [12–14], however, the effect of near-simultaneous ICU admissions (NSA) has neither been well described nor studied.

In this single-center study of patients admitted to an adult medical ICU, we aimed to examine the association between NSA patients with hospital and ICU mortality, compared to the control, i.e., non-NSA patients.

Materials and methods
Study design, population, and setting
We conducted a retrospective cohort study of consecutive adult patients, aged ≥ 18 years, admitted to the medical ICU of a tertiary academic referral center over five consecutive years. At the time of the study, the medical ICU was a closed unit of 24 beds, staffed by teams of intensivists, fellows, and residents, respiratory therapists, phlebotomists, pharmacists, and nurses throughout the 24 h. The medical ICU is a high-throughput, high acuity unit which takes only emergent, non-surgical, non-elective admissions. The clinical provider changes of shift happened every 12 h at 7 am and 7 pm. The day and night shift are referred to in the study as "day" and "night." Staffing is the same during the week, including weekends. There is always an attending physician intensivist in the ICU during the night shift. The overnight fellow helps the team with procedures, admissions, and responds to rapid response calls (Supplement Figure 1). During the study period, two teams staffed the morning shift and cared for up to 12 patients each. Each team consisted of one attending physician, one critical care fellow and, at least, one senior resident, and one junior resident along with ancillary pharmacist, respiratory therapists, and nursing staff. After the evening shift change, one dedicated, on-site overnight intensivist, a critical care fellow and two residents admitted new patients and covered for both teams. Only one of the two teams accepted admissions on each given day, and the admitting teams were alternating day-by-day. It was exceedingly unusual for the non-admitting team to accept admissions in a non-admitting day, regardless of how busy the other team was. The

Take-home message

The present study identifies the phenomenon of near-simultaneous ICU admissions (NSA), in which an ICU patient is being admitted immediately after a prior patient. The NSA phenomenon was common and was an independent risk factor for ICU and hospital mortality.

admission practices were uniform throughout the study period without significant process changes. The unit was aided by a Rapid Response Team (RRT) that was introduced years prior to the study period. An RRT team with a dedicated fellow during the day and night performed ICU consults outside the ICU and was able to refer ward admissions to the ICU teams. The RRT fellow was also covering and admitting for the ICUs during night shifts, with an overnight attending intensivist. Detailed information about the specific ICU [15] and the RRT [16] have been reported elsewhere. Nursing staffing in the medical ICU is not based on ratios; it depends on patient acuity. Acuity and workload are determined by a pre-defined set of objective and subjective indicators. For example, patients that require CRRT and mechanical ventilation are classified higher acuity based on the assessments and interventions that they require, and that would recommend more intensive (one-to-one) nursing. A schematic figure of the shift change can be found in Supplement Figure 1. De-identified data were securely stored [17]. The Mayo Clinic Institutional Review Board (IRB) approved the study (application number 13-003220).

Study variables
We collected data on patient demographics, date and time of ICU admission, location before the ICU admission, the need for invasive or non-invasive mechanical ventilation, the ICU and hospital lengths of stay and mortality, and the disposition location after the hospital discharge. We calculated the Acute Physiology and Chronic Health Evaluation (APACHE) III score [18] and Sequential Organ Failure Assessment (SOFA) scores within one and the first 24 h of ICU admission [19]. To assess the supply–demand mismatch that may require resource triage, we obtained meta-data variables for each ICU admission. These variables included the elapsed time since the last ICU admission (ETLA), the Time until the Next Future Admission (TNFA), the total count of daily ICU admissions, the time from the morning shift change until the index ICU admission, the admission source, and whether the admission occurred during night or during the time of morning pre-rounds and rounds, i.e., morning shift change until noon. The primary analysis categorically defined an NSA admission, any admission with an ETLA less or equal the 25th percentile of the ETLA

distribution (Supplement Figure 2). Non-NSA admissions occurred after the 25th ETLA percentile. We also analyzed the ETLA and TNFA as a continuous variable.

Outcomes

Primary outcomes included all-cause ICU and hospital mortality rates. Secondary outcomes included the ICU and hospital length of stay (LOS) and the hospital discharge location (i.e., home vs. nursing facility).

Statistical analysis

Since there is no accepted "Fracture Time Point" (FTP) cutoff in the literature, we examined and analyzed the ETLA as a continuous-time variable, in minutes. The data are summarized as mean with standard deviations (SD), median with interquartile ranges (IQR), or count and percentages when proper. We employed single and multiple, logistic, and linear regressions to assess the association between the NSA with the primary and secondary outcomes, respectively. To further understand the effect of the NSA on primary outcomes, we examined ETLA as a continuous variable. The study was powered to detect at least a 2% mortality in two proportions with baseline mortality of around 12%, with an alpha level of 5% and power of 80%. After examining the ETLA distribution, we selected to analyze the logarithmic transformation of the ETLA. For the adjusted outcomes, we performed multiple logistic (and linear regressions) where it applied to examine the adjusted Odds Ratio of NSA on each outcome (dichotomous, or continuous). We adjusted for severity of illness, overnight admission status, and admission source, admission during morning rounds, the daily census, and the number of new admissions.

We examined the effect modification of NSA with the severity of illness, as reflected in the APACHE III scores. We also assessed the statistical interaction of the daily admission volume, which is the total number of admissions that occurred on each shift. We interrogated the effect of the daily ICU census, the effect of weekends and the timing of educational conferences on APACHE-adjusted ICU mortality and near-simultaneous (NSA) admissions, and reported predicted mortalities by predictive margins post-estimation methods with interaction terms [20]. We calculated the post-estimation adjusted predicted mortalities at the average APACHE score. Moreover, we evaluated the statistical interaction of the admission source with the morning (am) rounds and NSA admissions. Finally, we examined the effect of NSA on APACHE III-adjusted hospital mortality when it occurs during the daytime or overnight shift. We performed post-estimation marginal analysis, at the means of each APACHE III stratified subgroups, to show the

post-estimation predicted severity-adjusted mortality for each subgroup. We performed two post hoc sensitivity analyses. The first examined the association of the TNFA with the ICU and hospital mortality. In other words, we tested if a near-future admission, interfered with an admission already in progress, by examining the TNFA association with hospital and ICU mortality. The second interrogated the interaction of overnight admissions and the Emergency Department versus another admission source. Missing data were excluded. All statistical analyses were performed with STATA® (StataCorp. 2018, Stata Statistical Software. Release 15.1 College Station, TX. StataCorp LP).

Results

We analyzed 13,234 ICU admissions during the study period. The median ETLA was 129 min (IQR 55–269). The first quartile of ETLA ($N = 3318$) of admissions fell within a 55-min window, the second quartile ($N = 3309$) between 55 and 129 min, the third quartile ($N = 3298$) between 129 and 269 min and the last quartile ($N = 3308$) more than 269 min apart. Table 1 outlines the baseline characteristics of the two cohorts, NSA, and control. The ETLA and log [ETLA] frequency distribution are shown in Supplement Figures 3 and 4a. Figure 1 summarizes the number and cumulative percentage of admissions per ETLA category.
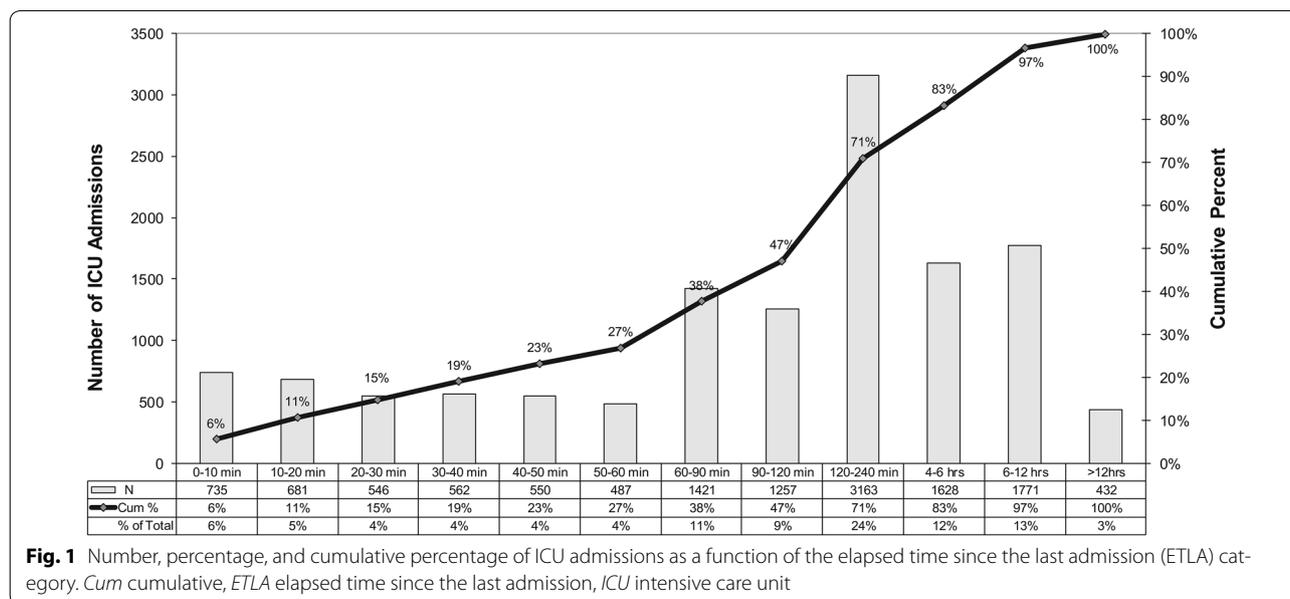
The adjusted models showed an inverse correlation between the logarithmic transformation of ETLA with ICU and both hospital and ICU mortality. For each incremental unit increase of the logarithmic transformation of ETLA [i.e., log (ETLA in minutes)], the average adjusted odds ratio (OR) of hospital mortality decreased by 0.93 (95% CI 0.89–0.97, $P = 0.001$). The corresponding effect on ICU mortality was 0.93 (95% CI 0.88–0.98, $P = 0.01$). For every incremental unit increase of the log (ETLA), the unadjusted ICU mortality OR gradually decreased by an added average OR of 0.95 (95% CI 0.90–0.99, $P = 0.05$). The unadjusted hospital mortality did not show statistical significance, OR 0.96 (95% CI 0.93–1.0, $P = 0.07$).

The mortality of the last admission was higher when the last admission occurred near-simultaneously with the immediately prior one. There was a dose–response effect (Fig. 2, Supplement Figure 4b). NSA had a higher unadjusted Odds Ratio (OR) of ICU death of 1.16 (95% CI 1–1.35, $P = 0.05$) and were associated with a 23% higher odds of adjusted ICU death (OR = 1.23, 95% CI 1.04–1.44, $P = 0.01$) and 20% higher odds of adjusted hospital death (OR = 1.20, 95% 1.05–1.35, $P = 0.004$) but not unadjusted hospital death of 1.11 (95% CI 0.99–1.24, $P = 0.06$). The Death OR were adjusted for APACHE scores, daily census, the number of new daily admissions, admission

Table 1 Baseline characteristics of the cohort

| Characteristic	Near-simultaneous admissions N = 3318				Controls N = 9916					P value
	N	Mean or %	Median	IQR	N	Mean or %	Median		IQR	
Age, years	3318	62.8	65.3	50.1	77.8	63.0	65.4	51.0	77.9	63.0	0.45
Female gender	1550	46.7%				4574	46.1%			0.56
ETLA, minutes	3318	25.30	24.13	11.0	39.32	256.8	185.9	108.6	335.0	256.8	< 0.001
APACHE III score (24 h after admission)	3318	68.62	67.00	51.0	84.00	68.9	67.0	51.0	84.0	68.9	0.59
APACHE III score, calculated at one hour after ICU arrival	3318	44.67	43.00	30.0	57.00	46.1	44.0	31.0	59.0	46.1	0.001
SOFA, day 1	3312	4.94	4.00	2.00	7.00	5.0	4.0	2.0	7.0	5.0	0.49
Mechanical ventilation, at any time during ICU stay	853	25.7%				2525	25.5%			0.78
Noninvasive ventilation, at any time during ICU stay	745	22.5%				2214	22.3%			0.001
Overnight admission	1612	48.6%				4710	47.5%			0.28
During morning rounds, i.e. 7:00AM–12:00PM	356	10.7%				1682	17%			< 0.001
ICU admission source										0.22
PACU	37	1.2%				94	1.0%			
ED	1472	44.4%				4518	47.4%			
Direct admission	742	23.06%				2027	21.3%			
Other ICU	139	4.32%				404	4.2%			
Ward and rest of locations	828	25.73%				2490	26.1%			
ICU census	3318	21.2	21	19	24	9916	20.7	21.0	18.0	23.0	< 0.001
Number of new admissions, per 12-h shift	3318	5.41	5.00	3.00	7.00	9916	4.3	4.0	2.0	6.0	< 0.001

APACHE acute physiology and chronic health evaluation, *ED* emergency department, *ETLA* elapsed time since the last ICU admission, *ICU* intensive care unit, *PACU* post-anesthesia care unit, *SOFA* sequential organ failure assessment

Fig. 1 Number, percentage, and cumulative percentage of ICU admissions as a function of the elapsed time since the last admission (ETLA) category. *Cum* cumulative, *ETLA* elapsed time since the last admission, *ICU* intensive care unit

during morning rounds, and overnight admission status versus daytime admission status (Supplement Table 1).

The effect of the elapsed time since the last admission (ETLA) on crude and adjusted mortality is shown in Table 2, Supplement Figure 4b, and Fig. 2. The "admission during morning rounds effect [21]" did not confound the effect of NSA on APACHE III adjusted hospital mortality. The effect of NSA on mortality was modified by the acute and chronic severity of illness, combined (Table 3).
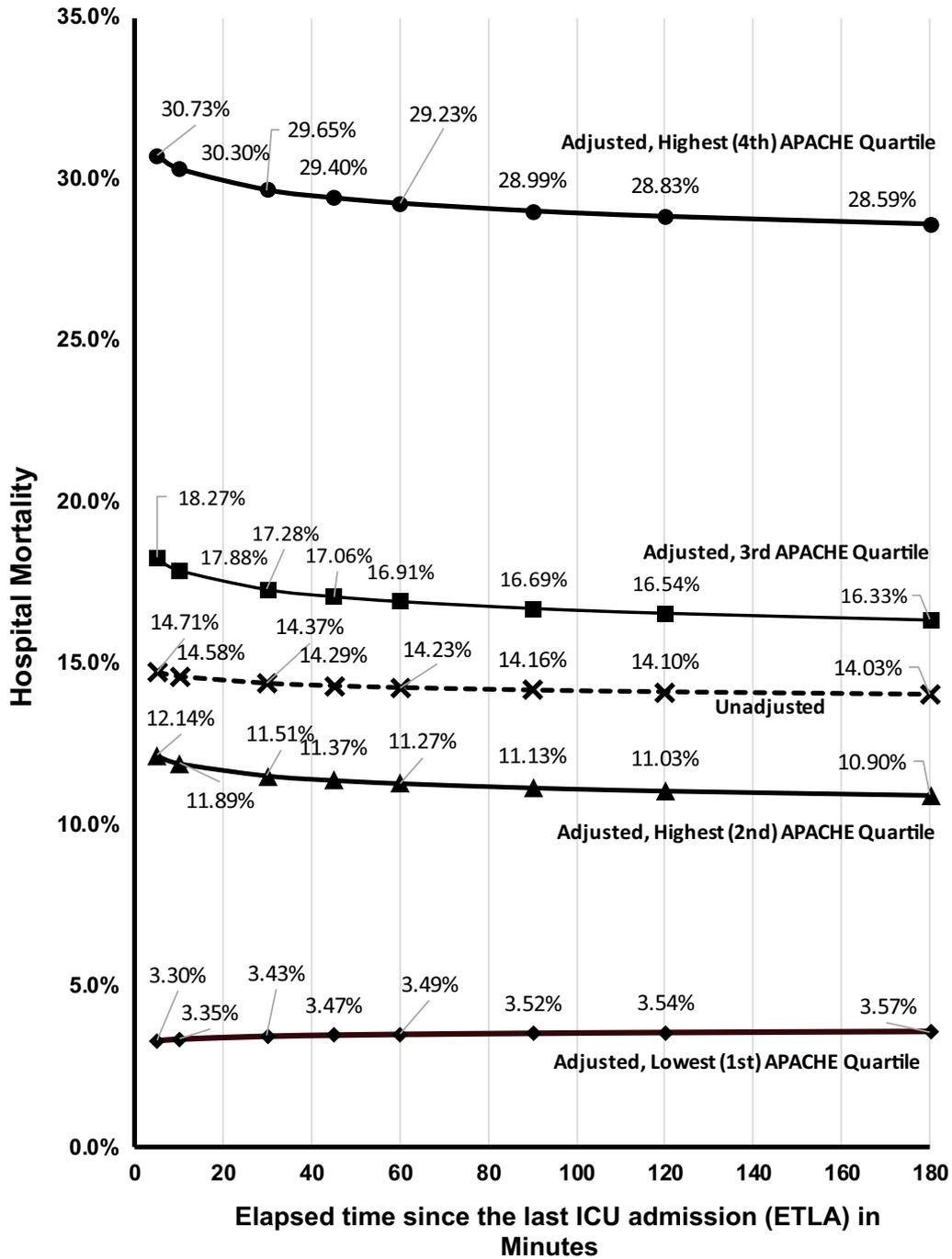
Fig. 2 Adjusted APACHE III at ICU arrival and hospital mortality and elapsed time since the last admission (ETLA), by illness severity. *APACHE* acute physiology and chronic health evaluation, *ETLA* elapsed time since the last admission, *ICU* intensive care unit

The number of new ICU admissions, per shift (Supplement Tables 1 and 2, Supplement Figure 5) did not significantly influence the effect of NSA on mortality, indicating that it is the clustering and the timing of new admissions matters more than the actual number of admissions. NSA had an adverse effect on severity-adjusted hospital mortality during both daytime and nighttime shifts (Supplement Tables 3a, 3b, 4). The ICU admission source influenced hospital mortality; however, the mortality effect of NSA remained, regardless of

Table 2 Crude and adjusted outcomes by ETLA cutoff, among NSA and control

	NSA ETLA interval					Control ETLA interval
	≤ 5 min N=413	5–15 min N=695	15–30 min N=890	30–55 min N=1320	All NSA N=3318	All control N=9915
Primary outcomes						
Crude hospital mortality	17.68% (73/413)	12.81% (89/695)	14.61% (130/890)	13.03% (172/1320)	13.98% (464/3318)	12.74% (1263/9913)
Model adjusted hospital mortality[b]	17.5% (14.0% to 21.1%)	13.2% (10.8% to 15.7%)	15.6% (13.3% to 18.0%)	13.5% (11.7% to 15.3%)	14.5% (13.3% to 15.7%)	12.6% (12.0% to 13.2%)
Unadjusted OR of hospital death[a]	1.47 (1.13 to 1.91) P=0.004	1.01 (0.80 to 1.27) P=0.96	1.17 (0.96 to 1.42) P=0.11	1.03 (0.87 to 1.22) P=0.77	1.11 (0.99 to 1.24) P=0.06	1 [Reference]
Adjusted OR of hospital death[a,c]	1.53 (1.16 to 2.02) P=0.002	1.06 (0.83 to 1.35) P=0.63	1.32 (1.07 to 1.62) P=0.009	1.10 (0.91 to 1.31) P=0.32	1.20 (1.05 to 1.35) P=0.004	1 [Reference]
Crude ICU mortality	10.65% (44/413)	6.91% (48/695)	7.98% (71/890)	6.67% (88/1320)	7.56% (251/3318)	6.59% (653/9915)
Adjusted ICU mortality[b]	10.4% (7.6% to 13.2%)	7.1% (5.2% to 8.9%)	8.5% (6.6% to 10.3%)	6.9% (5.5% to 8.2%)	7.8% (6.9% to 8.7%)	6.5% (6.1% to 7.0%)
Unadjusted OR of ICU death[a]	1.69 (1.23 to 2.33) P=0.001	1.05 (0.78 to 1.43) P=0.74	1.23 (0.95 to 1.59) P=0.11	1.01 (0.80 to 1.28) P=0.91	1.16 (1.00 to 1.35) P=0.05	1 [Reference]
Adjusted OR of ICU death[a,c]	1.73 (1.23 to 2.42) P=0.002	1.10 (0.80 to 1.50) P=0.57	1.35 (1.03 to 1.77) P=0.03	1.06 (0.83 to 1.35) P=0.63	1.23 (1.04 to 1.44) P=0.014	1 [Reference]
Secondary outcomes						
Difference in unadjusted ICU length of stay, days	0.41 (0.09 to 0.72) P=0.01	0.26 (0.02 to 0.51) P=0.04	0.03 (−0.19 to 0.25) P=0.79	0 (−0.18 to 0.19) P=0.99	0.12 (−0.01 to 0.24) P=0.07	0 [Reference]
Difference in adjusted ICU length of stay, days	0.44 (0.13 to 0.75) P=0.005	0.30 (0.06 to 0.55) P=0.015	0.11 (−0.11 to 0.33) P=0.322	0.04 (−0.14 to 0.23) P=0.64	0.16 (0.04 to 0.29) P=0.01	0 [Reference]
Difference in unadjusted hospital length of stay, days	−0.45 (−2.17 to 1.26) P=0.60	1.05 (−0.29 to 2.39) P=0.12	−0.34 (−1.53 to 0.86) P=0.58	−0.73 (−1.73 to 0.27) P=0.15	−0.22 (−0.90 to 0.47) P=0.54	0 [Reference]
Difference in adjusted hospital length of stay, days	−0.27 (−1.98 to 1.45) P=0.76	1.29 (−0.05 to 2.64) P=0.06	−0.02 (−1.22 to 1.18) P=0.97	−0.51 (−1.51 to 0.50) P=0.33	0.05 (−0.6 to 0.75) P=0.8	0 [Reference]
Unadjusted OR of home discharge (vs. facility)	0.78 (0.63 to 0.98) P=0.03	0.96 (0.81 to 1.13) P=0.56	0.97 (0.83 to 1.12) P=0.66	0.97 (0.85 to 1.09) P=0.57	0.94 (0.86 to 1.02) P=0.15	1 [Reference]
Adjusted OR of home discharge (vs. facility)	0.77 (0.61 to 0.96) P=0.02	0.95 (0.80 to 1.13) P=0.565	0.91 (0.78 to 1.06) P=0.22	0.91 (0.84 to 0.99) P=0.04	0.91 (0.84 to 1.00) P=0.04	1 [Reference]

APACHE acute physiology and chronic health evaluation, *ETLA* elapsed time since last admission, *min* minutes, *NSA* near-simultaneous admission, *ICU* intensive care unit, *OR* odds ratio

[Reference] denotes that those cells are the reference (base) for comparison to the other values

[a] The OR of death was calculated comparing with the reference of controls i.e. ETLA of > 55 min. Analysis was performed on hospital survivors only

[b] The adjusted hospital and ICU mortality, was predicted for the average APACHE III scores, daily census, number of new daily admissions, admission during morning rounds, and overnight admission status versus daytime admission status. The mortalities and conference interval are based on a post-estimation marginal analysis of the multiple logistic regression

[c] The adjusted hospital OR of death was adjusted for APACHE III score, daily census, number of new daily admissions, admission during morning rounds, and overnight admission status versus daytime admission status

Table 3 Effect-modification analysis[a] for the crude and adjusted primary outcomes for each APACHE III strata

	Near-simultaneous admissions		Control		OR to be NSA versus control[d] for each APACHE III strata s
	OR[a] hospital death	OR ICU Death	OR[a] hospital death	OR ICU death	
Lowest APACHE quartile					
Crude	0.79 (0.53–1.17) $P=0.239$	0.59 (0.31–1.11) $P=0.1$	1.00 [Reference]	1.00 [Reference]	0.37 (0.34–0.40) $P<0.001$
Adjusted[c]	0.80 (0.53–1.20) $P=0.281$	0.53 (0.28–1.03) $P=0.061$	1.00 [Reference]	1.00 [Reference]	
2nd APACHE III quartile					
Crude	2.55 (1.90–3.42) $P<0.001$	2.29 (1.51–3.47) $P<0.001$	2.17 (1.72–2.74) $P<0.001$	1.90 (1.36–2.65) $P<0.001$	0.33 (0.30–0.36) $P<0.001$
Adjusted[c]	2.50 (1.84–3.38) $P<0.001$	2.14 (1.39–3.29) $P=0.001$	2.08 (1.64–2.65) $P<0.001$	1.78 (1.27–2.51) $P=0.001$	
3rd APACHE III quartile					
Crude	4.20 (3.21–5.48) $P<0.001$	4.61 (3.22–6.60) $P<0.001$	3.30 (2.64–4.13) $P<0.001$	3.22 (2.36–4.41) $P<0.001$	0.35 (0.32–0.37) $P<0.001$
Adjusted[c]	4.01 (3.04–5.29) $P<0.001$	4.14 (2.86–6.01) $P<0.001$	3.18 (2.52–4.01) $P<0.001$	2.97 (2.15–4.09) $P<0.001$	
Highest APACHE III quartile					
Crude	8.83 (6.90–11.29) $P<0.001$	9.36 (6.74–13.00) $P<0.001$	7.11 (5.77–8.76) $P<0.001$	7.32 (5.48–9.79) $P<0.001$	0.30 (0.27–0.32) $P<0.001$
Adjusted[c]	8.58 (6.64–11.10) $P<0.001$	8.63 (6.15–12.10) $P<0.001$	7.01 (5.64–8.71) $P<0.001$	7.09 (5.27–9.53) $P<0.001$	

APACHE acute physiologic assessment and chronic health evaluation, *ETLA* elapsed time since last admission, *min* minutes, *NSA* near-simultaneous admission, *OR* odds ratio

[a] For the crude and adjusted hospital OR of death, the measure of effect modification based on a multiplicative scale of APACHE III * NSA (0/1) was the same, 1.03 (1.02–1.05); $P<0.001$. For crude and adjusted OR of death the multiplicative effect modification was also 1.03 (1.02–1.05); $P<0.001$

[b] The reference for each respective OR group is the Lowest APACHE Quartile controls. For example, the adjusted OR of ICU death for the highest 1 h APACHE III strata, is based on comparison with the lowest APACHE strata for the respective adjusted ICU OR of death with OR of 1

[c] The adjusted OR, was predicted based on daily census, number of new daily admissions, admission during morning rounds, and overnight admission status versus daytime admission status and ICU admission source for each of the APACHE III severity strata

[d] The OR in the last column, is not a mortality OR. It represents the OR for a given patient to be in the NSA group instead of the control group for the each APACHE quartile strata. The purpose of this column is to examine the proportion of NSA versus Controls among different severity strata

the admission source (Supplement Table 4). The overall ICU census (Supplement Tables 1, 2, 5) did not influence mortality. Admissions that occurred during the timing of the morning educational conferences of the fellows and residents had an independent association with hospital mortality. However, the NSA effect of mortality remained after adjusting for the educational conferences (Supplement Table 6). Weekend admissions did not appear to exert any effect on mortality (Supplement Table 7).

Regarding secondary outcomes (Supplement Tables 8–10), NSA was associated with a small increase in the adjusted ICU length of stay 0.16 days (95% CI 0.04–0.29, $P=0.01$) but not the adjusted hospital length of stay 0.05 (95% CI −0.6 to 0.75, $P=0.8$). Log[ETLA] had a linear association with the ICU length of stay (Supplement Table 8). In other words, the longer the time between the last admission, within the 55-min NSA timeframe, the shorter the ICU length of stay.

The NSA patients who did not die in the hospital, had unfavorable odds of home discharge versus placement in other care facilities, when compared to non-NSA patients who did not die in the hospital (adjusted OR=0.91, 95% CI 0.84–0.99, $P=0.04$). Log[ETLA] had a linear association with favorable odds of home discharge, in other words, the longer the time between since the last admission, within the 55-min NSA timeframe, the higher were the odds for home discharge (Supplement Table 10). The effect of the near-future admissions, as measured by the Time until the Next Future Admission (TNFA) from the index admission, did not have any association with ICU (unadjusted log[TNFA] OR=0.99, 95% CI 0.95–1.05, $P=0.8$; adjusted log[TNFA] OR=0.99, 95% CI 0.94–1.04, $P=0.6$), or hospital (unadjusted log[TNFA] OR=1.0 95% CI 0.96–1.04, $P=0.85$; adjusted log[TNFA] OR=0.99, 95% CI 0.95–1.05, $P=0.6$) mortality.

A final sensitivity analysis (Supplement Table 11) examined the interaction of the ICU admission source with the overnight admission, adjusting for the case-mix, unit census, and the number of new admissions. This analysis found that there is not statistical interaction of the overnight admission status and the admission source ($P=0.37$). Furthermore, the overnight admission

status was no longer associated with hospital mortality ($P = 0.17$), and the effect of the NSA remained on the hospital mortality (OR 1.16, 95% CI 1.05–1.31, $P = 0.03$).

Discussion

This large retrospective study in a tertiary, academic, closed, medical ICU, provides evidence that NSA for ICU admissions is linked with unfavorable patient outcomes. This statement is highlighted by the statistically higher odds of ICU and hospital death and lower odds of home discharge in the NSA patients. We showed a negative, linear association between the logarithmic ETLA and adverse outcomes (i.e., the *closer* the last ICU admissions is to the prior, the *worse* the outcomes).

Our findings suggest that NSA status in the ICU is an independent risk factor for mortality and adverse patient outcomes. The NSA effect on mortality appears to be modified by the severity of the disease (Table 3) [18], and is not confounded by the ICU admission source [22, 23], the time of admission (e.g., morning vs. evening) [21], or the overall ICU capacity strain [11–14, 24]. The NSA mortality effect was clear during both daytime and nighttime shifts. Night-time shift admissions had lower overall mortality, likely secondary to less proportion of patients admitted from the ward and outside ICU transfers [22, 25], however the NSA effect was still observed (Supplement Table 3a and 3b). We adjusted for the morning round effect since an earlier study [21] suggested that while the teams are engaged in morning rounds, newly admitted patients are receiving less attention during the initial time of admission, thus have higher mortality. We felt that this was a necessary adjustment in addition to the overnight status and the ICU source of admission [22]. When we adjusted for the statistical interaction of the overnight admission and the ED admission source, the effect of the overnight admission on mortality statistically disappeared. The statistical impact of NSA on hospital mortality remained intact, even after directly adjusting for the case-mix with the APACHE III score, the ICU admission source, census, the number of new admissions, and the interaction as mentioned above (Supplement Table 11). This model had the best fit of all prior models.

The NSA phenomenon is not a rare occurrence. One-fourth of all admissions arrived within less than 55 min between each other. We hypothesized that time-pressure mandates the need to [13] triage and ration resources. One would expect if there is a physician supply–demand mismatch, to see an added signal on worse outcomes when the staff are engaged in other activities such as educational conferences. A sensitivity analysis on Supplement Table 9 suggests that patients admitted during the resident and fellow educational conferences have higher

mortality, independently from the NSA effect. Since staffing is the same during weekends, as expected, we did not find a signal towards worse outcomes during weekends (Supplement Table 7).

We identified an ETLA fracture time point (FTP) of 55 min, beyond of which clinically relevant delays may occur which eventually trigger a sequence of late complications that irreversibly damage patients' vital organ systems (Table 2). There is a plethora of literature on the detriment of delays on various clinical syndromes (e.g., sepsis, trauma, cardiac arrest, lung injury) [26–33], or in cases of delays [34], or refusal to admit in the ICU [35].

Strain in the ICU can manifest in many shapes or forms [2, 12–14, 24]. Time-pressured teams are prone to a cascade of errors, including operational deviation errors, diagnostic performance and communication errors, (Supplement Figure 6) as well as fast decisions for limitations of life-sustaining therapies [36]. It can cause prescription errors [37], venous thromboembolism prophylaxis errors [24], higher hospital costs, increased postoperative complications [38–40], decreased staff satisfaction, increased complication rates and higher hospital length of stay [41]. Higher ICU strain, as measured by the proportion of new admissions, census, and acuity, is associated with increased mortality [12, 24, 42, 43].

Staffing is a crucial factor for patient outcomes. A recent, large study in the UK involving almost 50,000 patients, indicated the ideal patient-intensivist-ratio was 7.5 [40], which is significantly lower than the ratio of 12 in this study. We cannot, however, ascertain the optimal staffing ratio for the present cohort of 13 thousand admissions, due to the lack of a control group. It is possible that the NSA effect on outcomes could be improved with lower patient-to-intensivist ratios. However, the ideal patient–intensivist ratio is a moving target given the diversity of ICU types, staffing paradigms, case-mix, and countries [44, 45]. It is not surprising that the association between the high ratios of physician time availability contributing to low overall ICU strain and outcomes, has remained a field of controversy [46, 47]. However, contemporary ICU staffing models have some commonalities. All ICUs should have some NSA occurrences at different frequencies, and their operating mode is mostly non-adaptive to fluctuating time-pressure [41]. More importantly, in modern ICUs, the possible deleterious effects of NSA is not recognized. Therefore there are no known developed techniques or methodologies to deal with them.

Based on our results, we hypothesize that staffing during the NSA occurrences is a possible implicating factor. This hypothesis is further corroborated with additional evidence that admissions that occurred during educational conference hours (Supplement Table 6) and morning rounds [21] were associated with excess mortality.

Beyond staffing, a multitude of factors (Supplement Figure 6) may play several other roles, including communication, education, medication delivery systems, or even the mere lack of recognition of the NSA phenomenon, since it has not been previously described.

Prior studies have established that nursing ratios are key for patient outcomes [48–51]. In the present ICU, there is no bottleneck in nursing staffing, since the nurse staffing ratios are flexible and adaptive, in contrast to the physician staffing. Our findings suggest an expected mathematical distribution of the Elapsed Time between since the Last ICU Admission (ETLA, Supplement Figure 3 and 4a).

Possible solutions

Sustainable solutions are most likely to stem from addressing structural elements that influence NSA, vary among institutions [52–54]. It may be interesting to explore the supply-chains, the mechanisms of causes, and consequences of NSA rationing, such as the relationship with ED strain, hospital or outside transfers. Shedding light on these processes might allow fine-tuning of the ICU infrastructure or enhance the ability of other compensatory measures. For instance, if NSA leads to delay in the administration of antibiotics to a newly admitted ICU patient with sepsis, then an alternative would be the introduction of a dedicated subspecialized response teams, such as dedicated difficult airway team [55], or sepsis response team [56–58]. Successful quality improvement projects require funding, motivation, teamwork, leadership, and measurement systems which promote accountability [59]. The process for a successful quality improvement program might be more complicated and may need to employ a validated model like Donabedian's [52, 53]. For instance, in finding NSA rationing and starting corrective action, a live dashboard may supply real-time information. This technique, applied in an ED, enabled staff to avoid the adverse effects of ED crowding [60, 61]. Appropriate scheduling of low-severity or elective ICU admissions could buffer, intentionally delay and thus "spread out" NSA.

Team education based on a newly recognized NSA situation may improve clinicians' performance, as well as the speed and thoroughness of evaluation of staff performance during these periods. Communication strategy enhancements, such as safety huddles [62] may be implemented to strategize and tackle NSA situations, thus coordinated time and energy could then be redirected to time-sensitive, "golden" actions which are known to save lives.

Clinical relevance

The present study implies that NSA in ICU is associated with inequitable care, reflected in increased mortality, length of stay, and a decreased probability of home discharge among patients. Our findings suggest a simple, meaningful metric for ICU strain measurement linked to patient safety and outcomes. NSA can serve as a valuable process countermeasure for quality improvement projects [63, 64].

Limitations

The specific ETLA cutoffs of this analysis may differ among various ICUs, which are diverse regarding staffing models, acuity, the number of step-down beds, etc. This study reported an average FTP of 55 min. However, we hypothesize that each ICU may have an individualized average fracture time point (FTP) as this can vary according to differential staffing, patient volumes, and severity of acute illnesses, among other variables. The retrospective, observational nature of our study makes the level of evidence weaker than prospective investigations and randomized controlled trials. The single-center nature of the study limits its external validity and generalizability since ICU admission, and discharge policies are different between centers and between countries. APACHE scores measured at 24 h theoretically may be problematic in capturing the severity of illness on presentation; for example, an initial delay in central venous access and vasopressors may decrease the 24-urine output compared to the same patient without delays. We accounted for this by calculating the APACHE scores at one-hour as well (Supplement Figure 7). The patient volumes of the under-study ICU are higher and the severity lower than many other ICUs worldwide, potentially limiting external validity. The same limitation can also be a strength of this study, because NSAs could be causing harm in all ICUs, especially in higher-acuity ICUs, but are not as frequent and pass unnoticed. Endeavors to identify and describe this phenomenon in low volume ICUs may be misleadingly negative due to the low statistical power. We did not investigate the exact mechanisms of how NSA and rationing negatively correlate with patient outcomes. We did not have granular data on the precise nursing staffing for each bed. We do not have data on the interval between discharge and admission of a patient at the level of an individual bed. Most of these mediator variables, i.e., variables that can explain the exact mechanisms of how NSA ties to mortality (e.g., delayed endotracheal intubation) cannot be identified in the medical record. (Supplement Figure 6). The Time until the Next Future Admission (TNFA) was not statistically associated with increased mortality (Supplement Figure 8). We suggest that future ethnographic and quality improvement studies be conducted, to verify and elucidate mechanisms, causes, and effects of rationing.

Conclusion

Near-simultaneous ICU admission status is an independent and theoretically modifiable risk factor for mortality and adverse patient outcomes. NSA can serve as a process metric of temporal peak supply–demand mismatch of ICU resources, and a surrogate for undetected daily micro-triaging and rationing. These findings are hypothesis-generating. We highlight the need for more research and funding to externally confirm and further investigate this phenomenon.

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Compliance with ethical standards

Conflicts of interest

The authors report no research grants or conflicts of interest in this study.

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