Mortality among Patients Admitted to Strained Intensive Care Units

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Rationale: The aging population may strain intensive care unit (ICU) capacity and adversely affect patient outcomes. Existing fluctuations in demand for ICU care offer an opportunity to explore such relationships.

Objectives: To determine whether transient increases in ICU strain influence patient mortality, and to identify characteristics of ICUs that are resilient to surges in capacity strain.

Methods: Retrospective cohort study of 264,401 patients admitted to 155 U.S. ICUs from 2001 to 2008. We used logistic regression to examine relationships of measures of ICU strain (census, average acuity, and proportion of new admissions) near the time of ICU admission with mortality.

Measurements and Main Results: A total of 36,465 (14%) patients died in the hospital. ICU census on the day of a patient's admission was associated with increased mortality (odds ratio [OR], 1.02 per standardized unit increase; 95% confidence interval [CI]: 1.00, 1.03). This effect was greater among ICUs employing closed (OR, 1.07; 95% CI: 1.02, 1.12) versus open (OR, 1.01; 95% CI: 0.99, 1.03) physician staffing models (interaction *P* value = 0.02). The relationship between census and mortality was stronger when the census was composed of higher acuity patients (interaction *P* value < 0.01). Averaging strain over the first 3 days of patients' ICU stays yielded similar results except that the proportion of new admissions was now also associated with mortality (OR, 1.04 for each 10% increase; 95% CI: 1.02, 1.06).

Conclusions: Several sources of ICU strain are associated with small but potentially important increases in patient mortality, particularly in ICUs employing closed staffing models. Although closed ICUs may promote favorable outcomes under static conditions, they are susceptible to being overwhelmed by patient influxes.

Keywords: critical care; resource allocation; intensive care unit; physician staffing; regionalization

Intensive care units (ICUs) in the United States will encounter increased demand for critical care in the next two decades because of the aging of the American population (1). This sustained increase

AT A GLANCE COMMENTARY

Scientific Knowledge on the Subject

Patient outcomes may be adversely affected by the strain imposed on intensive care units (ICUs) because of the increased demand from the aging population. The effect of ICU strain near the time when patients are admitted is not well established. Variations in demand for ICU care offer an opportunity to explore relationships between ICU capacity strain and outcomes.

What This Study Adds to the Field

Our study shows that several sources of ICU strain are associated with small increases in mortality among patients. These effects are larger among ICUs using closed rather than open intensivist staffing models, suggesting that closed ICUs are vulnerable to being overwhelmed by patient influxes even though they may foster favorable outcomes under stable conditions. This suggests the need for caution if proposals to transfer more patients to closed ICUs are to be implemented.

in baseline demand will compound the effects of routine fluctuations in demand for critical care, such as from influenza epidemics and mass casualties. Concomitant increases in critical care supply are unlikely, due to projected staffing shortages and fiscal constraints (1–6). Thus, ICUs will be increasingly challenged to deliver high-quality care under conditions of increased capacity strain (7).

We reported that several measures of ICU capacity strain near the time that patients are discharged from ICUs may enhance the efficiency of critical care delivery without harming patients (8). However, mixed evidence exists regarding the effects of capacity strain closer to the time of ICU admission, when patients' trajectories are often determined by the care they receive. European studies have found associations between increased ICU workload and decreased patient safety (9, 10). By contrast, a large U.S. study found that one metric of strain, ICU census on the day of patients' admissions, was not associated with mortality (11).

We therefore sought, in the largest study of capacity strain to date, to determine whether several metrics of strain are associated with in-hospital mortality. We also sought to determine whether certain types of ICUs are more “elastic”—that is, better able to accommodate increases in strain without experiencing worse patient outcomes.

METHODS

Study Design

We performed a retrospective cohort study of patients admitted to U.S. ICUs included in the Project IMPACT database (Cerner Corporation,

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Kansas City, MO) from 2001 to 2008. IMPACT ICUs are nationally representative (12), and each uses trained data collectors and standardized web-based instruments to collect data. Prior research has demonstrated the validity of key fields (13).

The primary outcome was in-hospital mortality, and the secondary outcome was ICU mortality. The primary exposures were three metrics of ICU capacity strain measured on the day of a patient's admission: (1) standardized census, (2) acuity, and (3) admissions (*see* Table E1 in the online supplement). Each of these measures stems from a conceptual model of ICU capacity strain (7), and are independently associated with ICU physicians' and nurses' perceptions of daily workload, supporting their content validity (14).

ICU census was calculated within each ICU-year (defined as each ICU monitored for each January–December 12-mo period) as the number of patients in that ICU that day for at least 2 hours. To allow comparisons among ICUs of different sizes, census was standardized before analyses by subtracting the yearly mean daily census and then dividing by the yearly standard deviation. ICU acuity was calculated as the average predicted probability of death, measured using the mortality prediction model (MPM₀-III; *see below*), for the other patients in the ICU on the day of admission (*i.e.*, not including the index patient). To promote the stability of estimates, we restricted acuity measurements to days on which at least three patients contributed to ICU acuity. ICU admissions was calculated as the proportion of the day's census comprising new admissions that day.

Because strain may exert important effects on patient outcomes during more than just the day on which a patient is admitted, we also tested the impact of strain variables averaged during the first 3 days of the patient's initial ICU stay. We used the average effect over 2 days for patients whose ICU stays spanned only 2 days, and used the admission day strain score for patients who were in the ICU for 1 day.

Study Population

Eligible patients were admitted between April 1, 2001 and December 31, 2008 to U.S. ICUs included in IMPACT. We excluded patients from analysis for the following reasons: (1) ineligible for severity of illness assessment as calculated by the MPM₀-III; and (2) admission to the ICU with limitations on care beyond a simple do-not-resuscitate order. MPM₀-III is a validated measure of patient acuity and probability of in-hospital death (15, 16). To further augment the stability of estimates obtained from within-ICU analyses, we restricted the sample to ICUs contributing data to IMPACT for at least 1 year, and to ICUs contributing at least 20 patients per quarter-year. Last, we restricted analyses to patients' initial ICU stays during a hospitalization to avoid including the same patient more than once in the analysis if the patient is readmitted multiple times.

Outcomes

Our primary outcome was in-hospital death, which included patients dying during their initial ICU stay plus those dying after ICU discharge, including deaths in a step-down unit, on a general floor, or during an ICU readmission. The secondary outcome of ICU death included deaths occurring during the initial ICU admission plus patients discharged from the ICU in a moribund state.

Statistical Analysis

Primary and secondary outcomes were analyzed by hierarchical logistic regression in which ICU-year was modeled as a fixed effect to adjust for correlation of outcomes within ICUs and to prevent confounding by practice differences among ICUs or within ICUs over time. Before model building, we used locally weighted scatterplot smoothing to determine whether variables required transformation or could be entered

TABLE 1. CHARACTERISTICS OF PATIENTS AND STRAIN VARIABLES INCLUDED IN ANALYSES

Characteristic	Total (n = 264,401)	Died in Hospital (n = 36,465)	Did Not Die in Hospital (n = 227,936)	P Value
Sex, n (%) male	143,095 (54)	19,380 (53)	123,715 (54)	<0.001
Age, n (%)				<0.001
<65 yr	146,025 (55)	14,236 (39)	131,789 (58)	
65–74 yr	51,744 (20)	7,878 (22)	43,866 (19)	
74–84 yr	49,037 (19)	9,827 (27)	39,210 (17)	
≥85 yr	17,595 (7)	4,524 (12)	13,071 (6)	
Race, n (%)				<0.001
White	203,536 (77)	28,676 (79)	174,860 (77)	
Black	37,448 (14)	5,053 (14)	32,395 (14)	
Other	23,417 (9)	2,736 (8)	20,681 (9)	
Insurance status, n (%)				<0.001
Private	77,965 (30)	7,387 (20)	70,578 (31)	
Medicare	129,997 (50)	22,850 (63)	107,147 (48)	
Medicaid	22,408 (9)	2,554 (7)	19,854 (9)	
Self-pay	23,386 (9)	2,538 (7)	20,848 (9)	
Government/other	7,858 (3)	796 (2)	7,062 (3)	
Source of ICU admission, n (%)				<0.001
Emergency room	109,470 (41)	14,691 (40)	94,779 (42)	
Another hospital	16,365 (6)	2,741 (8)	13,624 (6)	
General care	33,155 (13)	8,358 (23)	24,797 (11)	
Step-down unit	7,409 (3)	2,034 (6)	5,375 (2)	
Procedure	86,585 (33)	6,515 (18)	80,070 (35)	
Skilled nursing or rehab	1,638 (1)	426 (1)	1,212 (1)	
Another ICU	4,501 (2)	1,096 (3)	3,405 (1)	
Other	5,198 (2)	595 (2)	4,603 (2)	
Type of ICU admission, n (%)				<0.001
Post-op, scheduled	57,615 (22)	2,769 (8)	54,846 (24)	
Post-op, unscheduled	32,804 (12)	4,453 (12)	28,351 (12)	
Medical	173,978 (66)	29,243 (80)	144,735 (64)	
Weekend admission, n (%) yes	81,512 (31)	12,472 (34)	69,040 (30)	<0.001
Predicted probability of death, median (IQR)	0.13 (0.16)	0.33 (0.25)	0.10 (0.12)	<0.001
Mechanical ventilation (any), n (%)	94,262 (36)	25,710 (71)	68,552 (30)	<0.001
Pressor use (any), n (%)	53,824 (20)	20,581 (56)	33,243 (15)	<0.001
Standardized census, median (IQR)	0.42 (1.18)	0.41 (1.20)	0.42 (1.18)	0.02
Acuity, median (IQR)	0.15 (0.09)	0.15 (0.09)	0.14 (0.09)	<0.001
Admissions, median (IQR)	0.25 (0.14)	0.24 (0.13)	0.25 (0.15)	<0.001

Definition of abbreviations: ICU = intensive care unit; IQR, interquartile range.

TABLE 2. ICU/ORGANIZATIONAL CHARACTERISTICS* FOR ICUs INCLUDED IN ANALYSES†

Characteristic	ICU-Years n (%)	Patients n (%)
ICU type		
Academic	149 (23)	63,209 (24)
City/county/state	30 (5)	10,023 (4)
Community	479 (73)	191,169 (72)
ICU location		
Urban	382 (58)	155,026 (59)
Suburban	189 (29)	68,058 (26)
Rural	85 (13)	40,642 (15)
ICU model		
Closed	47 (7)	19,025 (7)
Not closed	607 (93)	245,184 (93)
Number of ICU beds		
5–12	273 (42)	76,219 (19)
13–16	135 (21)	49,674 (19)
17–21	127 (20)	70,816 (27)
22–66	114 (18)	65,022 (25)
Night coverage		
Critical care physician	171 (26)	80,378 (30)
Attending/other physician	167 (25)	72,329 (27)
Fellow	44 (7)	22,652 (9)
Resident	203 (31)	64,434 (24)
Other	73 (11)	24,608 (9)
Critical care fellowship program	183 (28)	83,555 (32)
Affiliation with medical school	559 (85)	226,226 (86)

Definition of abbreviations: ICU = intensive care unit.

*n = 155 ICUs, 658 ICU-years.

†Data are presented by ICU-years at the beginning of the year. One hundred and seven hospitals included 155 ICUs from 2001 to 2008, for a total of 658 ICU-years. Seventy-three percent of hospitals had only one ICU.

linearly (17). Log transformation was required for admitted patients' MPM₀-III scores. Strain variables were entered as continuous variables and all three were included in each model. We explored two-way interactions between strain variables for each outcome.

We additionally explored potential interactions between strain variables and the following ICU characteristics: staffing model, patient volume, nighttime intensivist staffing, academic affiliation, and medical-surgical patient mix (see Table E5 for details on data coding).

Last, to assess whether relationships between strain and mortality may be mediated by relationships between strain and new decisions to limit life-sustaining therapy, we evaluated rates of such decisions among patients who died in the ICU across quintiles of day of admission strain, and across quintiles of average strain on Days 1–3. New decisions to limit life-sustaining therapies included any limitation on potentially life-sustaining interventions that was not present on ICU admission, new hospice enrollment, and, for patients who died in the ICU, the absence of a code for cardiopulmonary resuscitation on the day of or day preceding death. All analyses were conducted in SAS version 9.3 (SAS Institute Inc., Cary, NC). The study was considered exempt by the Institutional Review Board of the University of Pennsylvania (Philadelphia, PA).

RESULTS

Our cohort included 264,401 patients admitted to 155 ICUs in 107 hospitals (see Figure E1). Patients' mean age was 60 years (SD, 18), 54% were male, and 77% were white (Table 1). The mean predicted probability of death as measured by MPM₀-III at admission was 13% (SD, 16%), and there were 36,465 (14%) in-hospital deaths, of which 27,078 (74%) occurred during the patient's initial ICU stay. Most ICUs were located in community hospitals (73%) and in urban areas (58%) (Table 2). Closed physician staffing was employed during 48 ICU-years (7%), accounting for 19,025 patients.

The three metrics of capacity strain exhibited considerable variability on the days of patients' admissions (Table E2). Unadjusted associations between strain variables and in-hospital

and ICU mortality were all significant. Both standardized ICU census (odds ratio [OR] for a standardized unit increase, 0.99; 95% confidence interval [CI]: 0.97, 0.99) and admissions (OR for a 10% increase, 0.89; 95% CI: 0.88, 0.90) were associated with a decreased odds of in-hospital death, and acuity (OR for a 10% increase, 1.20; 95% CI: 1.18, 1.21) was associated with an increased odds for in-hospital death (Table E3). In adjusted analyses including patient-level covariates and all three strain variables without interaction terms, standardized ICU census on the day of admission was associated with increased odds that admitted patients would die in the hospital (OR for a standardized unit increase, 1.02; 95% CI: 1.00, 1.03). The proportion of ICU admissions was inversely associated with the odds of in-hospital death (OR for a 10% increase in admissions, 0.98; 95% CI: 0.96, 0.99), and ICU acuity had no significant effect (OR for a 10% increase in acuity, 1.00; 95% CI: 0.97, 1.02) (Table 3).

TABLE 3. LOGISTIC REGRESSION RESULTS FOR THE RELATIONSHIP BETWEEN STRAIN ON THE DAY OF ADMISSION AND ON DAYS 1–3 AND THE OUTCOME OF IN-HOSPITAL DEATH (MAIN EFFECTS)*

	Day 1		Days 1–3	
	OR (95% CI)	P Value	OR (95% CI)	P Value
Census	1.02 (1.00, 1.03)	0.02	1.03 (1.01, 1.05)	<0.01
Acuity	1.00 (0.97, 1.02)	0.69	1.00 (0.98, 1.02)	0.90
Admissions	0.98 (0.96, 0.99)	<0.001	1.04 (1.02, 1.06)	<0.001
Race				
White	1.00		1.00	
Black	0.87 (0.84, 0.91)	<0.001	0.87 (0.84, 0.91)	<0.001
Other	0.89 (0.84, 0.95)	<0.001	0.89 (0.84, 0.95)	<0.001
Sex				
Female	1.00		1.00	
Male	0.99 (0.96, 1.01)	0.28	0.99 (0.96, 1.01)	0.29
Insurance				
Private	1.00		1.00	
Medicare	1.43 (1.38, 1.48)	<0.001	1.43 (1.38, 1.48)	<0.001
Medicaid	1.06 (1.00, 1.13)	0.04	1.06 (1.00, 1.13)	0.04
Self-pay	1.06 (1.00, 1.13)	0.04	1.06 (1.00, 1.13)	0.05
Government/other	1.00 (0.91, 1.10)	0.96	1.00 (0.91, 1.10)	0.94
Source of ICU admission				
Emergency room	1.00		1.00	
Another hospital	1.16 (1.09, 1.22)	<0.001	1.16 (1.09, 1.22)	<0.001
General care	2.14 (2.06, 2.23)	<0.001	2.14 (2.06, 2.23)	<0.001
Step-down unit	1.82 (1.70, 1.95)	<0.001	1.82 (1.70, 1.95)	<0.001
Procedure	0.97 (0.91, 1.03)	0.32	0.97 (0.91, 1.03)	0.33
Skilled nursing or rehab	1.62 (1.41, 1.86)	<0.001	1.62 (1.41, 1.86)	<0.001
Another ICU	1.39 (1.28, 1.52)	<0.001	1.39 (1.28, 1.52)	<0.001
Other	0.86 (0.77, 0.97)	0.01	0.86 (0.77, 0.97)	0.01
Type of ICU admission				
Post-op, scheduled	1.00		1.00	
Post-op, unscheduled	1.06 (1.00, 1.13)	0.05	1.07 (1.00, 1.13)	0.04
Medical	1.53 (1.44, 1.64)	<0.001	1.53 (1.44, 1.64)	<0.001
Mechanical ventilation (any)	2.23 (2.16, 2.30)	<0.001	2.24 (2.17, 2.31)	<0.001
Pressor use (any)	3.26 (3.17, 3.36)	<0.001	3.27 (3.18, 3.37)	<0.001
Weekend admission (yes)	0.99 (0.96, 1.01)	0.31	1.00 (0.97, 1.03)	0.85

Definition of abbreviations: CI = confidence interval; ICU = intensive care unit; OR, odds ratio.

ORs for acuity and admissions represent a 10% increase in the variable; the OR for census represents a 1-unit change in standardized census.

*All models are adjusted for ICU-years and log MPM₀-III. To bolster risk adjustment beyond that provided by the MPM₀-III score, we also adjusted for whether patients were mechanically ventilated or required vasoactive infusions during their ICU stays. Because age is included in the MPM₀-III calculation, it was not adjusted for separately.

Similar results were observed for the secondary outcome of ICU death (Table E4).

There was a significant interaction between standardized census and acuity for both in-hospital death (P value for interaction < 0.01) and ICU death (P value for interaction $= 0.04$) (Figure 1), such that standardized ICU census was more strongly associated with death when the standardized census comprised sicker patients. For example, the OR for in-hospital death for each standardized unit increase in ICU census is 1.06 (95% CI: 1.01, 1.11) for the highest decile of ICU acuity, and 0.98 (95% CI: 0.93, 1.03) for the lowest decile of ICU acuity.

The effect of standardized census on in-hospital death was greater among ICUs with closed physician staffing models (OR, 1.07; 95% CI: 1.02, 1.12) than among ICUs with open physician staffing models (OR, 1.01; 95% CI: 0.99, 1.03) (P value for interaction $= 0.02$). Similar effects were noted for ICU death (Figure 2). Corresponding interactions between ICU capacity strain measures and the ICU characteristics of annualized patient volume, nocturnal intensivist staffing, academic affiliation, and medical-surgical case mix were all nonsignificant (Table E5).

Unadjusted analyses of ICU capacity strain averaged over the first 3 days of patients' ICU stays revealed similar results as in the primary analyses. Fully adjusted models also showed similar results for standardized census and acuity (Table 3 and Table E4). Further, when high proportions of new admissions occurred throughout the first 3 days of patients' ICU stays, these patients experienced higher odds of in-hospital death (OR for a 10% increase, 1.04; 95% CI: 1.02, 1.06) and ICU death (OR, 1.10; 95% CI: 1.08, 1.13). Both standardized ICU census and the proportion of new admissions, when averaged over Days 1–3 of patients' stays, were associated with larger increases in the odds of ICU mortality among ICUs employing closed versus open staffing models (P value for interaction $= 0.02$ in both cases; Table E6).

To assess the possibility that residual confounding might explain these results, we plotted the residuals from the fully adjusted models against each metric of capacity strain. No relationships were identified between the residuals and any strain metric (Figure

E2). We also found that differences in the probabilities of new decisions to limit life-sustaining therapy at times of high strain were unlikely to explain the main results (Table 4). For example, although standardized census was significantly associated with mortality, it was not significantly associated with the proportions of dying patients who had new life support withheld or withdrawn. Indeed, the only significant association between strain and such decisions regarding life support was that the proportion of new admissions on Days 1–3 was inversely associated with the probability of such decisions, despite being directly associated with the probability of mortality.

DISCUSSION

This study shows that several measures of how busy or strained the ICU is on a given day are independently associated with mortality among patients recently admitted to the ICU. Specifically, we found that routine variations in an ICU's standardized census were associated with patients' risk-adjusted odds of dying in the hospital, particularly when that standardized census consists of sicker patients. The proportion of the standardized census composed of newly admitted patients, who tend to be more resource intensive, was also associated with mortality.

Small changes in mortality risk, when estimated precisely (i.e., with narrow CIs) as in this study, may have a large cumulative impact and may be important to ICU patients and providers. Indeed, when planning randomized trials in critical care, some investigators have set the clinically important difference at 2% despite the fact that such thresholds require the enrollment of large patient samples (18). Of note, these effects manifested with the routine fluctuations in strain already being observed in U.S. ICUs. More extreme surges in demand may pose greater risks for admitted patients, and the hazards of high-capacity strain may manifest more frequently because of the aging population.

A second major finding is that these effects of ICU capacity strain are roughly constant across ICUs with different patient

Figure 1. Interaction between standardized census and acuity for the outcomes of in-hospital and intensive care unit (ICU) death. Acuity is presented in deciles and census is presented as a continuous variable.

Figure 2. Interaction between standardized census and physician staffing model for the outcomes of in-hospital and intensive care unit (ICU) death.

volumes and nighttime staffing models, but are particularly large among ICUs employing closed daytime intensivist staffing. We hypothesized such effect modification because one of the scarcest ICU resources is the time that physicians have available to evaluate and manage patients (19). Thus, during times of high strain, less time can be allocated to individual patients in a closed staffing system, whereas the strain is distributed among more practitioners in an open staffing system.

This observation creates a paradox: although closed ICUs may provide optimal care under average or static conditions (20, 21), they may be the most inelastic under conditions whereby large fluctuations in demand for services exist. Thus, recommendations for closed staffing of all ICUs and to regionalize the provision of adult critical care (22–27) may concentrate the impact of capacity strain on intensivist-led ICUs.

Prior studies of singular metrics of ICU capacity strain have produced mixed results. Some investigators have found that occupancy or average nursing workload on the days that patients are admitted to adult and neonatal ICUs are associated with increased mortality (9, 10, 28). Other studies found that elevations in ICU census and occupancy were not associated with adverse outcomes (11, 29). Our study of the largest and most diverse sample of ICUs to date suggests that previous results may have been influenced by the staffing models found in the ICUs examined, and may have been limited by failing to account for the acuity of other patients in the ICU or by limiting analyses to strain on the day of admission.

Third, this study suggests that strain does not affect mortality by increasing the frequency of decisions to limit life support. We had hypothesized that in the face of a need to create open beds, clinicians might more expeditiously recommend limitations on life support. We found no evidence for such an effect. Indeed, the proportion of new admissions was associated with significantly reduced odds of decisions to limit life support, perhaps due to the

time required for family meetings that lead to such changes in care. Therefore, future studies are needed to identify how strain influences other processes of care that could explain the observed effects.

Finally, we found that patients admitted to ICUs on days with an increased proportion of new admissions had lower odds of in-hospital and ICU death, whereas those exposed to sustained increases in new admissions during the first 3 days of their ICU courses had significantly higher mortality. This combination of findings suggests that the seemingly protective relationship of being admitted on a high-admission day is due to lower acuity patients being admitted when more beds or other resources are available. However, it appears that even such lower risk patients can be harmed when exposed to subsequent high-admission days, which may divert resources, including clinicians' time, from their care.

This study should be interpreted in light of potential limitations. First, ICUs that participate in IMPACT are not randomly selected (30). However, the sample reflects the distribution of U.S. ICUs regarding size, location, and organization type. For example, unlike other large ICU databases, more than 70% of IMPACT ICUs reside in nonacademic, community-based hospitals, as is true of U.S. critical care more broadly (31). Further, our results reflect within-ICU contrasts averaged across ICUs, considerably reducing the possibility of ICU-level confounding (32).

A second potential limitation is that our results could be influenced by incomplete risk adjustment. We aimed to overcome this by adjusting not only for MPM₀-III, but also by source of ICU admission and use of mechanical ventilation and vasopressors. We further explored the possibility of residual confounding by examining relationships between model residuals and strain variables, to determine whether the degree of incomplete risk adjustment was associated with strain. No such relationships were identified. Thus, even if residual confounding by illness severity was present, its magnitude appears to be similar across levels of

TABLE 4. PREDICTED PROBABILITIES (95% CONFIDENCE INTERVAL) FOR DECISIONS TO LIMIT LIFE-SUSTAINING THERAPY AMONG INTENSIVE CARE UNIT DEATHS BY QUINTILES OF STRAIN ON THE DAY OF ADMISSION AND ON DAYS 1–3

	Day of Admission	Days 1–3
Census		
Quintile 1*	0.778 (0.770, 0.786)	0.782 (0.774, 0.790)
Quintile 2	0.780 (0.775, 0.786)	0.782 (0.777, 0.787)
Quintile 3	0.782 (0.777, 0.787)	0.782 (0.777, 0.786)
Quintile 4	0.783 (0.778, 0.789)	0.781 (0.776, 0.787)
Quintile 5	0.785 (0.778, 0.793)	0.781 (0.773, 0.789)
	<i>P</i> = 0.24	<i>P</i> = 0.81
Acuity		
Quintile 1*	0.784 (0.776, 0.792)	0.783 (0.775, 0.792)
Quintile 2	0.783 (0.777, 0.789)	0.783 (0.776, 0.789)
Quintile 3	0.782 (0.777, 0.787)	0.782 (0.777, 0.787)
Quintile 4	0.781 (0.776, 0.786)	0.781 (0.776, 0.786)
Quintile 5	0.779 (0.771, 0.788)	0.780 (0.772, 0.788)
	<i>P</i> = 0.51	<i>P</i> = 0.64
Admissions		
Quintile 1*	0.778 (0.770, 0.785)	0.798 (0.791, 0.806)
Quintile 2	0.780 (0.774, 0.785)	0.790 (0.784, 0.795)
Quintile 3	0.781 (0.777, 0.786)	0.783 (0.778, 0.788)
Quintile 4	0.784 (0.778, 0.789)	0.775 (0.769, 0.780)
Quintile 5	0.787 (0.778, 0.796)	0.762 (0.753, 0.770)
	<i>P</i> = 0.17	<i>P</i> < 0.001

* Quintile 1 = lowest quintile; quintile 5 = highest quintile.

strain, and hence would bias our comparisons of high- versus low-strain days toward the null.

Third, our patient exclusion criteria, implemented to ensure robust estimates, could have impacted ICUs differently, thereby biasing comparisons. However, analyses of patients with measurable severities of illness who were excluded versus included showed no differences in their severities of illness; similar null effects were found individually among open and closed ICUs.

We cannot rule out the possibility that the differential effect seen among open and closed ICUs is attributable to selective exclusion from closed ICUs of low-acuity patients during periods of high strain. However, if the results were attributable to the selective admission of patients who were sicker in unmeasured ways, these effects should be diluted (i.e., get smaller) when we include strain on days after the admission day in the exposure variable. Instead, we observe larger effects when examining average strain across the first 3 days of an ICU strain. This evidence of a dose-response relationship between strain and mortality increases the likelihood that the relationship is causal. Nonetheless, we cannot rule out the possibility that low-performing ICUs selectively adopt closed staffing models in an effort to improve, and that the mechanisms underlying the original low performance (e.g., poor communication) are exacerbated when strain rises.

Additional limitations regard what we have not measured. We were unable to determine whether ICUs that differ in other important ways, such as in their use of multidisciplinary care teams (33), clinical protocols (34), favorable nurse-to-patient ratios (10, 35), and trained clinical pharmacists (36, 37), are differentially susceptible to the influences of ICU capacity strain. Similarly, we could not evaluate outcomes among patients who were denied ICU admission because of capacity strain. Finally, future work is needed to determine how ICU strain influences important outcomes other than mortality.

Together, these data suggest that the outcomes for critically ill patients are influenced not only by their own characteristics and by the static features of the ICUs to which they are admitted, but also by dynamic measures of how strained a given ICU happens

to be near the time of admission. Yet it seems that not all ICUs are equally elastic regarding these capacity strains, with those using open physician staffing models being more elastic and better able to withstand the normal variations of capacity strain than are those using closed staffing models. Future work is needed to identify other ICU characteristics that influence their abilities to withstand strains on capacity, to determine what processes of care account for such differences in elasticity, and to explore whether such care processes can be transported from more elastic to less elastic ICUs.

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