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Association between strained capacity and mortality among patients admitted to intensive care: A path-analysis modeling strategy☆

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ABSTRACT

Purpose: To evaluate the associations between strained ICU capacity and patient outcomes.
Methods: Multi-center population-based cohort study of nine integrated ICUs in Alberta, Canada. Path-analysis modeling was adopted to investigate direct and indirect associations between strain (available beds ≤1; occupancy ≥95%) and outcomes. Mixed-effects multivariate regression was used to measure the association between strain and acuity (APACHE II score), and both acuity and strain measures on ICU mortality and length of stay.
Results: 12,265 admissions comprise the study cohort. Available beds ≤1 and occupancy ≥95% occurred for 22.3% and 17.0% of admissions. Lower bed availability was associated with higher APACHE II score ($p < 0.0001$). The direct effect of ≤1 available beds at ICU admission on ICU mortality was 11.6% (OR 1.116; 95% CI, 0.995–1.252). Integrating direct and indirect effects resulted in a 16.5% increased risk of ICU mortality (OR 1.165; 95% CI, 1.036–1.310), which exceeded the direct effect by 4.9%. Findings were similar with strain defined as occupancy ≥95%. Strain was associated with shorter ICU stay, primarily mediated by greater acuity.
Conclusions: Strained capacity was associated with increased ICU mortality, partly mediated through greater illness acuity. Future work should consider both the direct and indirect relationships of strain on outcomes.

1. Introduction

Strain on intensive care unit (ICU) capacity is conceptually defined as a dynamic discrepancy between the availability of ICU resources (i.e., beds, ventilators, clinicians) and demand to admit and provide high-quality care for patients with critical illness [1,2]. Strained capacity is perceived among clinicians to be encountered more frequently due to growing demand for and relatively fixed supply of critical care services [1].

Strained ICU capacity may contribute to suboptimal quality of care [1,3], may modify clinician behaviors and care processes [4,5], and may increase susceptibility for adverse events [6], premature ICU discharges [7], unplanned readmissions [8] and mortality [9]. Recent observations suggest sustained strain may negatively impact clinician well-being [10,11].

Numerous factors contribute to strain including bed availability [4,12], bed turnover rate, patient acuity [9], bedside workload [13,14] and bed-block (i.e., discharge limitation) [15]. Selected measures of strain have been characterized (e.g., census, acuity, new admissions [8,9]); however, studies have not specifically evaluated the impact of strained ICU capacity in a large integrated health jurisdiction where the care of critically ill patients is coordinated across ICUs [16,17]. Moreover, their generalizability to health regions with considerably lower numbers of ICU beds is uncertain [18-20]. Finally, most studies have examined the direct relationships (typically logistical regression) between

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measures of strain and outcomes [8], but have seldom explored potential indirect effects of strain (e.g., mediation through illness acuity) on outcomes. Prior work has suggested a complex relationship may be indirectly mediated between strain and ICU care processes [5].

To begin to characterize this complex relationship between strain measures and patient outcomes, we performed a population-based cohort study using path-analysis integrating both the direct and indirect effects strain may exert on outcomes. The work was conducted in a large geographically-defined healthcare system serving a population of approximately 4 million residents in Alberta, Canada (estimated 7.9 ICU beds/100,000 population [20]), where ICUs regularly operate at near or full capacity with often marginal reserves to manage planned admissions, day-to-day variability, and unanticipated surges in demand.

We hypothesized that increased strain on ICU capacity would be associated with greater risk of ICU and hospital mortality. We further hypothesized that strained capacity may exert both direct and indirect influences on risk of death. As such, we hypothesized that direct effects will be shown with selected strain measures (i.e., occupancy, bed availability), while indirect effects will be mediated through variation in illness acuity.

2. Materials and methods

2.1. Study design, setting, and population

This was a population-based cohort study of 9 adult ICUs in Alberta, Canada between June 19, 2012 and December 14, 2014. All ICUs were mixed medical/surgical units in the two major cities in Alberta: Calgary (4 units) and Edmonton (5 units). Of these, 2 are classified as academic/tertiary, 2 as tertiary, and 5 as metropolitan/community ICUs (Supplementary Tables 1 and 2). All included ICUs were staffed by board certified intensivists, had in-house coverage by clinical associates or resident trainees, and had availability of after-hour intensivist coverage. All consecutive adults (age ≥ 15 years) admitted to any of the 9 ICUs were eligible for inclusion.

2.2. Data sources

We analyzed data from a provincial clinical information system (*eCritical Alberta*) coupled with a data warehouse and clinical analytics system (*TRACER Alberta*) (http://www.albertahealthservices.ca/assets/about/scn/ahs-scn-sb-cc-ecritical.pdf). During the study period, six of the study ICUs were implemented on *eCritical*. As such, these ICUs were did not contribute data for the full study period (Supplementary Tables 1 and 2). For the purpose of ensuring the reliability of data from newly initiated ICUs, we omitted the first month contributed to *eCritical*.

eCritical is composed of a bedside system (MetaVision™, iMDsoft, Germany), which provides for full electronic inter-disciplinary clinical documentation and collation of demographic, diagnostic/case-mix (i.e., comorbidity, diagnostic classification, surgical status, Acute Physiology and Chronic Health Evaluation [APACHE] II and III score), laboratory and device data (i.e., monitor, ventilator, vasoactives, renal replacement therapy). *TRACER* provides a comprehensive, multimodal and integrated data repository of patient-specific ICU data enabling creation of reports and specific data extracts for administrative, quality, and research purposes. *eCritical* and TRACER are governed by rigorous methods of data quality assurance and audit. The *eCritical* platform functions within Alberta Health Services (AHS), governed by a provincial multi-disciplinary executive leadership group. *eCritical/TRACER* has previously been used to support health services research [4,21]. Charlson comorbidity index score was ascertained by linkage of *eCritical* data with AHS Discharge Abstract Data (DAD) housed in the AHS Data Repository for Reporting [22].

2.3. Exposures and outcomes

Primary exposure was ICU strain, defined as instantaneous bed availability (≤1, ≤2 or ≤3 beds available at the time of patient admission) and as instantaneous bed occupancy (≥90%, ≥95% proportion of occupied beds at the time of patient admission). While additional measures of strain have been proposed [8,9], we have focused this study specifically on "bed-side" factors (i.e., occupancy, bed availability) in recognition that these are more likely to have immediate influence on clinician decision-making about ICU admission, rather than "resource-side" factors present in the ICU (i.e., new admissions, average acuity, bedside workload). APACHE II score was automatically calculated from data acquired by eCritical in the first 24 h following ICU admission. Primary outcome was all-cause ICU mortality. Secondary outcomes were hospital mortality and ICU length of stay (LOS).

2.4. Statistical analysis

Data were initially explored descriptively. Normally or near normally distributed data were reported as means with standard deviations (SD) and compared by Student's *t*-test. Non-normally distributed continuous data were reported as medians with inter-quartile ranges (IQR) and were by Mann–Whitney *U* test. Categorical variables were compared using the Chi-squared test.

2.4.1. Path-analysis model

We developed a path-analysis model to estimate the magnitude and significance of hypothesized causal associations (direct, indirect and the total combined effect of both) between measures of strained capacity and outcomes (Fig. 1). We first measured the association of measures of strained capacity on patient illness severity at ICU admission (APACHE II score) using a mixed-effects linear regression model, adjusted for covariates that could confound the association between illness severity and strained capacity: age, sex, pre-existing comorbid disease, site (city, hospital type [academic, tertiary and community]), primary diagnostic category, admission category (i.e., medical, neurological, surgical, trauma), surgical status (i.e., elective, emergency), and after-hours admission (i.e., between 22:00 to 7:00). The intent of this analysis was to understand how much the relative contribution of the admission APACHE II score was attributed to strained ICU capacity, assuming random intercepts across the 9 ICUs. We then measured the direct effects of strain measures on ICU mortality, hospital mortality and ICU LOS using a mixed-effects logistic/log-linear regression model, similarly adjusted for the covariates listed above. To integrate the total effect of both the

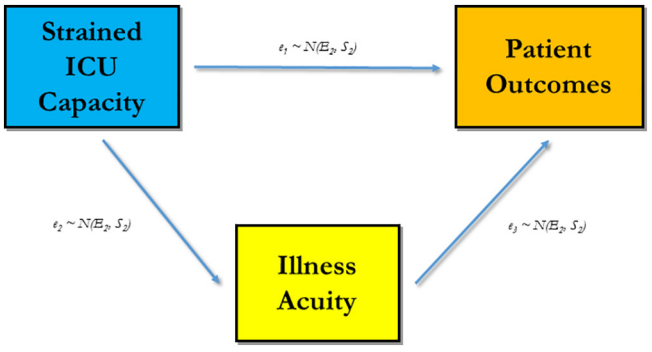

Fig. 1. Path diagram showing the hypothesized causal direct and indirect associations between strain, illness acuity and outcomes. **Footnote**: After modeling, we extracted three pairs of parameters (E_i, S_i), $i = 1,2,3$ (estimate, standard error), which were used to describe the direct and indirect associations of ICU capacity strain to patient outcomes (i.e., ICU mortality). In detail, we used normal distribution $N(E_1, S_1)$ to describe the direct association, and $N(E_2, S_2)$ and $N(E_3, S_3)$ to describe the indirect associations. We did a simulation with 1 million replications to calculate indirect and total (integrated direct and indirect) effects using parameters and the following algorithm: **Algorithm 1**. Estimate indirect and total (integrated) effect of ICU capacity strain.