Measuring and Mitigating Patient Safety Threats Due to Strains on ICU Capacity

Principal Investigator: Scott D. Halpern, M.D., Ph.D.

Perelman School of Medicine, University of Pennsylvania

Other key team members: Brian L. Strom, M.D., M.P.H., Sarah J. Ratcliffe, Ph.D.

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Project Officer: Kay Anderson, (301) 427-1555, kay.anderson@ahrq.hhs.gov

STRUCTURED ABSTRACT

Purpose: To develop and validate objective measures of strains on ICUs' capacities to provide high-quality care

Scope: One prospective study to develop and validate a parsimonious model of ICU capacity strain, and three retrospective cohort studies to measure the effects of this model of strain on patient outcomes and processes of care

Methods: The prospective study was a single-center study in which 11 objectively measured candidate markers of ICU capacity strain were regressed against ICU physicians' and nurses' perceptions of strain on corresponding days. The retrospective studies were performed among roughly 150 ICUs across the U.S. that were included in the Project IMPACT database.

Results: Three measures of ICU capacity were validated: ICU census, proportion of the census comprising new admissions, and average severity of illness of the census (acuity). We found that higher levels of strain during the first 3 days of an ICU stay were associated with slight increases in patient mortality and substantial decreases in appropriate use of venous thromboembolism prophylaxis. Strain on the day of ICU discharge was associated with shorter preceding ICU length of stay, slightly increased risk of ICU readmission, and no change in hospital length of stay or mortality.

Key Words: ICU capacity strain, ICU staffing model, processes of care

Purpose

Recent studies have identified several Intensive Care Unit (ICU)-level factors that influence patient outcomes, such as the use of clinical protocols, the volume of patients cared for, physician staffing models, and the presence of multidisciplinary teams on rounds. Beyond these “fixed” ICU characteristics, it is also possible that time-varying ICU-level factors play a role in patient care and ICU outcomes. We define "ICU capacity strain" as a set of temporally varying influences on an ICU’s ability to provide high-quality care for everyone who is or could become a patient in that ICU on that day.

Several factors may relate to how busy the ICU is on a given day, including objective metrics such as the ICU’s census, the proportion of new admissions that day, the mean severity of illness of patients in the ICU, and bed occupancy. Factors external to the ICU may also influence ICU capacity strain, such as the demand for ICU beds in the emergency department or the availability of ward beds to serve as a release valve for the ICU. However, which of these potential markers of ICU capacity strain track with front-line clinicians’ perceptions of strain, and which are associated with patient outcomes and processes of care, remains unclear. Finally, it is also uncertain whether relationships between strain and outcomes are preserved across ICUs or differ in magnitude among different types of ICUs. Clarifying these relationships was the central goal of this career development award, as doing so holds great promise for improving the quality of care provided to the nation’s most seriously ill patients.

SCOPE

Increasing demand for critical care due to an aging population, with limited potential for a comparable expansion of critical care supply, may strain intensive care units' (ICUs') abilities to provide high-quality care in an equitable fashion. The core premise of this work is that ICUs function like a balloon – able to accommodate patients in greater numbers and rising acuity only up to a point, after which care delivery deteriorates (i.e., the balloon pops). We term this concept "ICU Capacity Strain." This concept breeds a number of empirical questions that this grant sought to answer, including (1) what factors strain an ICU's capacitance (what factors increase pressure inside the balloon?), (2) what threats does high strain pose to patients who are or could be cared for in the ICU (what happens if the balloon pops?), and (3) what organizational characteristics of ICUs enable some to accommodate increasing strain better than others (why are some balloons more elastic than others?)?

METHODS

Prospective Study

We performed a prospective cohort study of patients admitted to the Medical Intensive Care Unit (MICU) of the Hospital of the University of Pennsylvania from June 15-December 14, 2010. This tertiary-care hospital serves as a regional referral center for patients in all specialties, including medical critical care. The MICU is a 24-bed closed unit staffed by critical care attending physicians, fellows, and medical residents that admits adults with nonsurgical diagnoses from the emergency department, from other hospital units, and as interhospital transfers.

We administered a questionnaire about perceptions of capacity strain on a daily basis to charge nurses and physician arbitrators during the study period, as detailed below. The results of this questionnaire were merged, by calendar day, to an analytic database containing 11 MICU-level and hospital-level variables that we identified *a priori* as potential contributors to ICU capacity strain. The rationale for studying these particular parameters was that we believed their daily variability could place uneven demand on constant resources and staffing and, therefore, strain the ICU's capacity. We then assessed relationships between these candidate measures of strain and the "perceived strain score," defined as the perception of strain identified by the charge nurse and physician arbitrator. Charge nurses oversee the nurse staffing and bed management issues for the entire unit. One of the two ICU attending physicians on service functions as the arbitrator, with authority to accept or decline outside hospital transfer requests and to prioritize beds for patients already within the hospital (including those in the emergency room).

We developed a questionnaire about perceptions of ICU capacity strain with the input of a focus group of critical care specialists and refined it during a 2-week pilot administration. The final questionnaire consisted of five questions, four of which inquired about the perceived adequacy of the supply of specific ICU resources that day (ICU beds, nurses, respiratory therapists, and residents and/or mid-level practitioners). Respondents indicated how many more or fewer units of each of these resources than were available would be necessary "to provide optimal care to all patients today." The questionnaire specified that respondents should consider all patients already admitted to the MICU as well as those for whom a request for a MICU bed had been made. The final question asked respondents to rate their overall perception of ICU capacity strain on that day using a scale from 1 to 10. We specifically asked about strain on the capacity of the ICU as a whole, not on an individual practitioner.

We performed multivariable analyses to determine which resources were deemed necessary by survey respondents in times of higher perceived capacity strain. To do so, we utilized mixed effects linear regression models, in which the perceived strain score was the dependent variable and the independent variables included each resource about which we inquired (numbers of ICU beds, nurses, respiratory therapists, and residents and/or mid-level practitioners). We selected these variables for inclusion a priori, and all were included in the final models. We built separate models for charge nurse and physician arbitrator responses. Because providers may differ in their general perceptions, we standardized perceived strain scores by individual for all multivariable models. Standardized values were calculated as the difference between the raw number and the mean of that provider's responses across days, divided by the standard deviation of all responses given by the same provider. Standardized perceived strain scores account for the heterogeneous distributions of responses by the same individual.

We performed unadjusted analyses of each candidate capacity strain variable with physicians' and nurses' subjective strain scores using mixed effects linear regression models. We then performed a multivariable analysis to identify those strain variables that were independently associated with physicians' and nurses' perceived strain scores, again using standardized scores. To do so, we utilized Least Angle Regression, a model-building algorithm that considers parsimony as well as predictive accuracy. This algorithm sequentially fits models in which predictors are added to or dropped from the active set, and the coefficients of each included variable are updated. The algorithm is similar to forward stepwise regression in that it begins with each candidate variable's coefficient equal to zero and finds the predictor most highly correlated with the outcome. Successive variables are then entered, individually and in tandem, to assess improvement in model fit while penalizing the model for each extra variable added. Thus, only covariates that contribute more to prediction than would be expected for any given covariate are retained. This process is repeated until the value of the likelihood ratio test decreases from the prior model. This final model is considered to be the optimal set of linearly independent predictors.

Retrospective Studies

We conducted three separate retrospective cohort studies within the Project IMPACT database. The cohorts included patients admitted to U.S. ICUs included in the Project IMPACT database (Cerner Corporation, Kansas City, Missouri), which prospectively collects information on patients in 186 ICUs at 125 hospitals in the U.S. Project IMPACT is a voluntary and fee-based clinical information system comprising a large and diverse sample of ICUs that is commonly used for critical care outcomes research. Data collectors who are certified by Project IMPACT capture detailed clinical information at each site from the time of ICU admission until hospital discharge. Because we were granted permission to use a specially prepared version of Project IMPACT that retained real date and time stamps for all patients' ICU admissions and discharges, we had a unique opportunity to determine how patients co-inhabiting ICUs influenced each other's outcomes. Previous work has shown that IMPACT ICUs are nationally representative and has demonstrated the validity of key fields.

In the first study, we sought to determine whether transient increases in ICU strain near the time of ICU admission influence patient mortality and to identify characteristics of ICUs that are resilient to surges in capacity strain. For this purpose, we conducted a retrospective cohort study of 264,401 patients admitted to 155 U.S. ICUs from 2001-2008. We used logistic regression to examine relationships of the three measures of ICU strain found to be most closely related to clinicians' perceived strain in our prospective study (census, average acuity, and proportion of new admissions) with in-hospital mortality. We evaluated strain on the day of ICU admission as well as strain average during the first 3 days of ICU admission. 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 – by evaluating statistical interactions between ICU characteristics and strain measures on the outcome of in-hospital mortality.

In the second study, we sought to determine how the same three metrics of ICU capacity strain (ICU census, new admissions, and average acuity) measured on days' of patients' discharges influence these patients' ICU length of stay (LOS) and post-ICU discharge outcomes. For this purpose, we conducted a retrospective cohort study from 2001-2008 among 200,730 adults discharged from 155 IMPACT ICUs to hospital floors. We evaluated associations between ICU capacity strain metrics and discharged patients' ICU LOS, 72-hour ICU readmissions, subsequent in-hospital mortality, post-ICU discharge LOS, and hospital discharge disposition using hierarchical logistic and linear regression as appropriate.

For the third study, we used multivariable logistic regression to examine the relationships between ICU capacity strain and appropriate venous thromboembolism prophylaxis (VTEP) and stress ulcer prophylaxis (SUP). The eligible cohort included 229,296 patients admitted to 155 ICUs between April 1, 2001, and December 30, 2008. All patients in the Project IMPACT database during the study period who were admitted without bleeding were considered appropriate for VTEP. Patients receiving mechanical ventilation for more than 48 hours were considered appropriate for SUP.

Results

Prospective Study

The study period included a total of 183 days, with 127 days eligible for surveys (i.e., non-weekend and non-holiday days). Of 254 possible surveys, 226 (89%) were completed by 18 charge nurses and 17 physician arbitrators on 122 of the 127 (96%) eligible days. Among all clinician ratings on these days, the median perceived strain score was 5 (IQR 3-7). When stratified by type of respondent (charge nurse or physician arbitrator), the median and IQR were the same. There was moderate correlation between the scores of physicians and nurses on the same day (ICC = 0.45, 95% CI 0.30 to 0.60). Higher perceived strain scores reported by charge nurses were associated with their perceived need for additional ICU nurses ($p<0.001$). Higher physician scores were associated with their perceived need for additional beds ($p=0.004$) and residents and/or mid-level practitioners ($p=0.004$).

Among both nurses and physicians, higher ICU census was associated with higher perceived strain. Among nurses, higher mean APACHE III score and census on the general medical wards were also associated with higher perceived strain. A higher number of admissions to the ICU was associated with lower perceived strain. The proportions of variance explained by the most parsimonious models predicting the physician and nurse perceived strain scores (as measured by the model R^2) were 0.067 and 0.130, respectively.

Retrospective Studies

In the first study, evaluating relationships between ICU capacity strain on day 1 and days 1-3 of the ICU stay with in-hospital mortality, 36,465 (14%) patients died in the hospital. 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)). Similar results were observed for the secondary outcome of ICU death. Averaging strain over the first 3 days of patients' ICU stays also 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)).

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), 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. 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.

In the second study, 200,730 eligible patients survived their initial ICU admission and were discharged to a hospital floor or step-down unit. Among such patients, 3.2% underwent an ICU readmission within 72 hours, 4.0% died in the hospital following their initial ICU discharge, and 63.3% were ultimately discharged directly home from the hospital.

Many of the foregoing measures varied considerably across the included ICUs (data not shown), consistent with the diversity of ICUs included in Project IMPACT.

The strain variables were not highly correlated with each other (ICU census and ICU admissions (R=0.23), ICU census and ICU acuity (R=-0.03), and ICU admissions and ICU acuity (R=-0.095)), enabling their joint inclusion in multivariable models. After additional adjustment for patient characteristics, each strain variable was inversely associated with ICU LOS (all p<0.001). There was a significant interaction between ICU admissions and ICU acuity (p=0.015) such that the effect of admissions on the decline in ICU LOS was greater during times of higher acuity. Hospital LOS after ICU discharge was longer among patients discharged on days with higher census (p=0.002), shorter among patients discharged on days with increased admissions (p<0.001), and not significantly associated with ICU acuity (p=0.076).

Elevations in all three strain variables were associated with greater odds of 72-hour ICU readmission in the fully adjusted model. For every one unit change in census, there was a 3% increased odds of 72-hour ICU readmission (p=0.030). Similarly, 10% increases in ICU admissions and ICU acuity corresponded to 3% (p=0.053) and 5% (p=0.017) increased odds of ICU readmission, respectively.

None of the capacity strain variables were associated with increased odds of subsequent in-hospital mortality or with decreased odds of being discharged directly home from the hospital. Being discharged on days with increased admissions was associated with lower odds of subsequent in-hospital mortality (OR 0.97, 95% CI (0.94-0.99)) and higher odds of being discharged directly home from the hospital (OR 1.01, 95% CI (1.00-1.03)). There were no significant two-way interactions between any two strain variables when assessing dichotomous outcomes.

To illustrate the magnitude of the regression findings, increases in all three strain variables from the 5^{th} to the 95^{th} percentiles of their respective distributions resulted in a 6.3-hour (95% CI: 5.3–7.3) reduction in expected ICU LOS for patients surviving their initial ICU stay, and a 2.0-hour (95% CI: 1.0–3.0) decrease in expected post-ICU-discharge hospital LOS. Thus, corresponding increases in the three ICU capacity strain variables resulted in an overall reduction of 8.3 hours in expected total hospital LOS (Table 4). In addition to this decrease in total hospital LOS, increasing all three strain variables from the 5^{th} to the 95^{th} percentiles resulted in a 1.0% (95% CI: 0.6-1.5%) increase in the probability of experiencing an ICU readmission within 72 hours of ICU discharge and no significant change in mortality or disposition.

Similar to our primary analyses, analyses accounting for ICU transfer practices yielded null associations between the three strain variables and mortality: ICU census (OR 1.02, 95% CI (0.99-1.05)), admissions (OR 0.98, 95% CI (0.95-1.00)), acuity (OR 1.00, 95% CI (0.96-1.04)). Similar results also were produced in the other eight secondary analyses. We found no consistent evidence that the effects of strain on ICU LOS varied significantly by an ICU's physician staffing model or academic affiliation.

In the third study, of 776,905 patient-days eligible for VTEP, adherence for prophylaxis was 39.5% for pharmacologic, 48.7% for mechanical, and 67.7% combined. In the SUP group, prophylaxis was given on only 47.8% of eligible patient-days.

In fully adjusted models, VTEP adherence decreased as both the proportion of new admissions (OR 0.91, 95% CI 0.90 - 0.91) and ICU census (OR 0.97, 95% CI 0.97-0.98) increased. Adherence was also lower among weekend admissions (OR 1.03, 95% CI 1.01-1.06). The ICU acuity (OR 1.00, 95% CI 0.99-1.01) was not associated with changes in odds of receiving prophylaxis. In the SUP group, none of the strain measures were associated with odds of receiving prophylaxis in adjusted analyses.

Medical, nonoperative patients had significantly lower odds of receiving prophylaxis compared to routine surgical patients for both VTEP (OR 0.68, CI 0.65-0.72) and SUP (OR 0.78, 95% CI 0.68-0.90). Being mechanically ventilated was associated with significantly higher odds of receiving VTEP (OR 4.00, 95% CI 3.85-4.17). Increased severity of illness of the patient as measured by MPM_0-III was associated with increased odds of receiving appropriate VTEP (OR 3.95, 95% CI 3.38-4.62) but with decreased odds of receiving appropriate SUP (OR 0.74, 95% CI 0.58-0.95).

While adjusting for patient level demographic variables, we also found that Black compared to White race was associated with decreased odds of receiving VTEP (OR 0.95, 95% CI 0.92-0.98) but not for SUP (OR 1.00, CI 0.91 - 1.09). In the VTEP group, having Medicare (OR 0.96, 95% CI 0.92-0.99) or Medicaid (OR 0.92, 95% CI 0.89-0.96) compared to private insurance was associated with lower odds of receiving prophylaxis. This pattern was consistent in the SUP group for patients with Medicare (OR 0.90, 95% CI 0.82-0.99) and Medicaid (OR 0.89, 95% CI 0.80-0.99). Female gender had no statistically significant effect on odds of receiving either VTEP (OR 1.02, 95% CI 1.00-1.04) or SUP (OR 0.97, 95% CI 0.91-1.04).

Conclusions

Taken together, these studies show that daily measures of the ICU census, the average severity of illness in the ICU, and the number of new admissions to the ICU are conceptually sound and empirically valid measures ICU capacity strain, and are related to ICU patient flow, processes of care, and outcomes. Specifically, the data suggest that critically ill patients' outcomes 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 and the time of discharge. Yet it seems that not all ICUs are equally elastic in regards to 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.

The data also suggest that the circumstances under which patients are discharged from ICUs to hospital floors vary considerably from day to day within each ICU and that these variations affect patient flow without changing short-term patient outcomes. This suggests that rather than causing the rationing of beneficial care, strain occurring near the time of ICU discharge spurs providers to reduce their provision of what appears to be low-value critical care by critically re-examining patients' needs for ICU-level care and transferring those who could be equally well managed outside the ICU setting.

LIST OF PUBLICATIONS

The core publications emanating directly and exclusively from this grant are:

1. Halpern SD. ICU capacity strain and the quality and allocation of critical care. *Current Opinion in Critical Care* 2011; 17: 648-657.
2. Wunsch H, Wagner J, Herlim M, Chong DH, Kramer A, Halpern SD. ICU occupancy and mechanical ventilator use in the United States. *Critical Care Medicine* 2013; 41: 2712-2719. PMID: 23963122.
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4. Gabler NB, Ratcliffe SJ, Wagner J, Asch DA, Rubenfeld GD, Angus DC, Halpern SD. Mortality among patients admitted to strained intensive care units. *American Journal of Respiratory and Critical Care Medicine* 2013; 188: 800-806.
5. Kerlin MP, Harhay MO, Cooney E, Ratcliffe SJ, Halpern SD. Objective factors associated with physicians' and nurses' perceptions of intensive care unit capacity strain. *Annals of the American Thoracic Society* 2014; 11: 167-172.
6. Weissman GE, Gabler NB, Brown SES, Halpern SD. Capacity strain reduces adherence to prophylaxis guidelines in the intensive care unit. (under review)

The following additional publications were made possible, in whole or part, by the career development support Dr. Halpern received from this grant:

7. Thabut G, Christie JD, Fournier, M, Kremers WK, Halpern SD. Survival differences following lung transplantation among US transplant centers. *JAMA* 2010; 304:53-60.
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29. Brown SES, Ratcliffe SJ, Halpern SD. Assessing the utility of ICU readmissions as a quality metric: An analysis of changes mediated by residency work-hour reforms. *Chest* (in press)