Trauma Surge Index: Advancing the Measurement of Trauma Surges and Their Influence on Mortality

Peter C Jenkins, MD, MSc, Caroline R Richardson, MD, Edward C Norton, PhD, Colin R Cooke, MD, MSc, Mousumi Banerjee, PhD, Avery B Nathens, MD, PhD, FACS, Mark R Hemmila, MD, FACS

BACKGROUND: Increases in trauma patient volume and acuity, such as during mass casualty events, can overwhelm hospitals, potentially worsening patient outcomes. Due to methodological limitations, the effect of trauma surges on clinical outcomes remains unclear, so hospitals have not prepared for such events in an evidence-based manner. The objective of this study was to develop a new measure of hospital capacity strain corresponding to trauma admissions and to examine the relationship between trauma surges and inpatient mortality.

STUDY DESIGN: Using trauma registry data from hospitals across the United States and Canada (2010 to 2011), we developed the Trauma Surge Index (TSI), a measure of capacity strain that controls for variation in hospital admission volume and patient acuity. Using the TSI and an established definition of mass casualty events, we quantified hospital surges and entered each measure as an exposure variable in separate risk-adjusted mortality models.

RESULTS: Using the TSI method, we observed that patients admitted during high-surge periods display significantly increased mortality compared with patients admitted during low-surge periods (odds ratio [OR] = 2.05; 95% CI, 1.36−3.10), and patients with firearms injuries were particularly at risk (OR = 7.29; 95% CI, 2.13−24.91). Using mass casualty event criteria, we found no difference between the mortality of patients admitted during trauma surges and nonsurge periods (OR = 0.94; 95% CI, 0.88−1.01).

CONCLUSIONS: We demonstrate the TSI, which is a novel method that identified periods of high-capacity strain in hospitals associated with increased trauma patient mortality. Our newly developed TSI method can be implemented by hospitals and trauma systems to examine periods of high-capacity strain retrospectively, identify specific resources that might have been needed, and better direct future investments in an evidence-based manner. (J Am Coll Surg 2015; 221:729−738. © 2015 by the American College of Surgeons)

Traumatic injury is among the largest contributors to morbidity and mortality worldwide.[1] Although considerable advances have occurred in the treatment of traumatic injury, the potential impact of hospital conditions on its delivery remains poorly understood. Previous studies suggest that trauma surges lead to poor clinical outcomes when

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From the Department of Surgery, Indiana University, Indianapolis, IN (Jenkins), Department of Health Management and Policy (Norton), Department of Economics, National Bureau of Economic Research (Norton), Center for Healthcare Outcomes and Policy (Norton, Cooke, Banerjee, Hemmila), Departments of Family Medicine (Richardson, Cooke), Biostatistics (Banerjee), and Surgery (Hemmila), University of Michigan, Ann Arbor, MI, and Division of General Surgery, Department of Surgery, University of Toronto, Sunnybrook Health Sciences Centre, Toronto, Ontario, Canada (Nathens).

Correspondence address: Peter C Jenkins, MD, MSc, Methodist Hospital, 1604 N Capitol Ave, B250, Indianapolis, IN 46202. email: pjenkins1@iuhealth.org

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Abbreviations and Acronyms

ISS = Injury Severity Score
MCE = mass casualty event
OR = odds ratio
ROC = receiver operating characteristic
TQIP = Trauma Quality Improvement Program
TSI = Trauma Surge Index
TSL = Trauma Surge Load

characterized by rapid increases in trauma patient volume and acuity.[2-6] During these surges, the health care needs of patients exceed available resources, thereby disrupting hospital operations and causing them to falter.[7] As projected shortages in the health care workforce constrain the health care system and the projected incidence of traumatic injury increases, overwhelming events are likely to become increasingly prevalent in the United States.[8-14] For health care systems outside of the United States, the threat of becoming overwhelmed by unexpected events is even greater due to the limited available resources.

To date, efforts to prepare for unexpected trauma surges have relied primarily on expert opinion rather than objective data.[7,15,16] For example, policy directives that address surge capacity have focused on isolated hospital factors, such as bed availability, despite the fact that not all hospitals suffer from a shortage of hospital beds. Meanwhile, individual hospitals remain poorly equipped to identify historic periods of high-capacity strain and assess the specific resources needed during those periods.[17] In addition, the needs of individual hospitals have not been well-differentiated from the specific needs of trauma systems. Understanding these factors is essential to distribute patients and resources effectively among multiple hospitals when faced with capacity strain. These knowledge gaps largely exist due to historic methods used to identify and measure hospital capacity strain.

The most extensively studied form of trauma surge is mass casualty events (MCEs), and those events have been identified using a minimum surge threshold, such as 10 trauma patient admissions in a 24-hour period.[3,6,18] However, this definition produces only a crude estimate of capacity strain, without accounting for patient injury severity or variation in hospital capacity, principle determinants of health care resource demand. Therefore, MCE does not specifically address whether low-volume and high-volume trauma centers display differences in their thresholds that define when these centers become overwhelmed.

In this study, we demonstrate a new measure of trauma surge that accounts for patient injury severity based on data from the Trauma Quality Improvement Program of the American College of Surgeons. Our approach is applicable to a broad range of hospitals by controlling for the annual volume and acuity of trauma patients treated in each specific hospital. To compare our measure and the established MCE surge measure, we further examined the relationship between trauma surges and inpatient trauma mortality in a broad range of hospitals across the United States and Canada. Notably, we observe differences in the ability of each respective measure to detect clinically relevant trauma capacity strain.

METHODS

Study design

We conducted a retrospective cohort study of trauma patients treated at hospitals participating in the Trauma Quality Improvement Program (TQIP). Primary exposure variables included two different measures of trauma patient capacity strain—Mass Casualty Event criteria and the Trauma Surge Index—and the primary outcome of interest was inpatient trauma mortality.

Data source

The cohort consisted of patients meeting inclusion criteria for the American College of Surgeons TQIP.[19] The TQIP is a consortium of trauma centers across the United States and Canada that collects clinical trauma registry data using standardized definitions and provides risk-adjusted performance improvement reports to its participants. Trained trauma registry personnel collect prehospital, emergency department, operative, intensive care, and hospital data for all adult trauma patients with an Abbreviated Injury Scale Score of ≥ 3 in at least one body region resulting in an Injury Severity Score (ISS) ≥ 9. Regular audits ensure data validity for the program's clinical registry. In addition to standard clinical information, the dataset for this study included date and time of hospital admission as well as discharge. These data were provided in an encrypted fashion through collaboration with the American College of Surgeons to ensure compliance with the Health Insurance Portability and Accountability Act. The TQIP analytic methods have been described in detail previously.[19]

Study population

We included patients discharged from a TQIP participating center between January 2010 and December 2011. We excluded patients who lacked records for date and time of admission to the emergency department. We also excluded patients who presented to emergency departments without signs of life, defined as an initial systolic blood pressure of 0 mmHg, heart rate of 0 beats/min, and Glasgow Coma Scale motor score of 1.[20]

Exposure variables

We used two measures of trauma surge capacity strain, criteria for an MCE and a Trauma Surge Index (TSI), each measured at the time of hospital admission of each patient.

Mass casualty event

We used an established MCE criteria cited in previous literature. These criteria consisted of at least 10 patients admitted to a single hospital within a 24-hour period or 3 severely injured patients with ISS >15 admitted to a single hospital within a 3-hour period.[3,6] These criteria were previously used to evaluate the relationship between trauma surges and inpatient trauma mortality.[6]

Trauma Surge Index

To assess trauma capacity strain, we developed a measure using 3 variables: patient ISS, time and date of hospital admission, and a unique hospital identifier. The resulting measure, the TSI, was constructed to meet 3 goals. First, TSI reflects the injury severity of patients admitted during trauma surges. Second, TSI can be applied to a broad range of hospitals by controlling for variation in annual trauma admission volume and patient acuity. Third, TSI addresses the statistical challenges unique to low-volume trauma centers.

For each patient in the dataset, we sought to characterize the demand for hospital resources by other patients during the period of hospital admission. For each index patient, we aggregated the ISS of patients admitted 24 hours before and 24 hours after that patient, excluding the ISS of the index patient. We labeled the aggregated ISS as the trauma surge load (TSL), and we calculated it for each patient in the dataset. By assessing the 24-hour period before admission, we identified patients who were admitted toward the conclusion of trauma surges, and we identified patients who were admitted at the beginning of such surges by examining the 24 hours after admission. In addition, we initially selected 24-hour periods because we believe that the initial 24 hours is a critical period in the initial resuscitation of the trauma patient and a 24-hour period includes at least one change of shift for hospital staff, a process that can prove particularly challenging during periods of high-capacity strain.

Next, we sought to control for hospital factors, annual patient volume and acuity, and address the statistical challenge posed by low-volume hospitals. Previous studies of nontrauma hospital surges have controlled for hospital variation using *z* scores or coefficients of variation, but those measures required data with a normal distribution.[13,21] Trauma admission rates did not display a normal distribution, particularly in low-volume centers where 0 or 1 patient admission per day was the norm. As a result, *z* scores and coefficients of variation did not accurately reflect the distribution of daily trauma admission rates in these hospitals. Instead, the TSI used nonparametric values (median and interquartile range) to account for non-normal, highly skewed distributions of daily admission rates. Therefore, we determined annual median TSL scores and interquartile ranges for each hospital after calculating TSL scores for each patient. We then calculated the difference between the TSL score of the index patient and median TSL score of the corresponding hospital. Only patients admitted during periods with an above-average TSL were assigned positive values. Finally, we divided that value ($TSL_{patient} - TSL_{median}$) by the hospital TSL interquartile range. The interquartile range is a nonparametric measure of variance that is valid in both low- and high-volume hospitals. Using median values and interquartile ranges, the resulting measure or the TSI is similar to a coefficient of variation, which is calculated using mean values and SDs. Stata code to calculate the TSI will be made available on request, and formulas for the TSL and TSI are in Appendix 1 (online only; available at: http://www.journalacs.org).

Risk adjustment

When modeling the impact of trauma surge on mortality, we adjusted the probability of death for patients using the ISS, the motor component of the Glasgow Coma Scale, age, sex, race, initial systolic blood pressure in the emergency department, mechanism of injury, and transfer status. Additionally, we controlled for the following hospital-level variables: American College of Surgeons verification level, total number of beds, number of ICU beds, and teaching status.

Analysis

First, we tested the bivariate association between mortality and trauma surge using both MCE and TSI measures in logistic models. The TSI was rounded down from a continuous variable to integer values to facilitate interpretation of the surge to mortality relationship. Negative TSI values and TSI values of 0 were collapsed, representing periods of lower than normal trauma capacity strain or periods of average capacity strain, respectively. Consistent with the TQIP mortality model, systolic blood pressure was transformed into a quadratic variable to account for nonlinearity.[20] Next, we performed clustered multivariable logistic regression using 2 models to examine mortality, 1 with MCE as the surge measure and the other with TSI. Because patients admitted to the same hospital are correlated, we clustered at the hospital level. This clustering accounted for correlation at both the hospital level

Table 1. Patient Characteristics (n = 230,621)

Characteristics	All patients	Low-surge admissions*	High-surge admissions*	p Value[†]
Age, %				0.75
16–25 y	17.9	17.9	17.5	
26–35 y	13.0	13.0	10.9	
36–55 y	26.8	26.8	28.0	
56–65 y	13.1	13.1	13.0	
66–75 y	9.9	9.9	10.6	
76–85 y	11.8	11.8	14.2	
Older than 85 y	5.6	5.6	4.5	
Not recorded/unknown	2.1	2.1	1.5	
Female, %	35.4	35.4	40.4	0.16
Race, %				0.25
White	71.9	71.9	76.5	
African American	13.8	13.8	10.9	
Asian	1.7	1.7	0.6	
Other	9.5	9.5	8.7	
Unknown	3.3	3.3	3.3	
Initial systolic blood pressure in emergency department, n, mean (SD)	136 (33)	136 (33)	135 (35)	0.35
Motor component of the Glasgow Coma Scale, %				0.03
1	8.8	8.8	3.9	
2	0.4	0.4	0.6	
3	0.4	0.4	0.6	
4	1.6	1.6	2.7	
5	3.3	3.3	3.0	
6	82.1	84.6	82.1	
Not recorded/applicable, %	3.4	3.4	4.5	
Patient injury severity using ISS 98, mean (SD)	16.8 (9.1)	16.8 (9.1)	16.7 (9.2)	0.91
Transferred from other facility, %	31.7	31.7	15.6	<0.001
Mechanism of injury, %				0.51
Pedestrian struck	6.3	6.3	5.4	
Motor vehicle collision	24.7	24.7	28.6	
Cut/pierce	2.9	2.9	2.7	
Fall	40.6	40.6	38.6	
Firearm	5.0	5.0	3.0	
Motorcyclist	7.4	7.6	8.9	
Pedestrian other	0.4	0.4	0.3	
Other	12.7	12.7	12.7	

*Low-surge admissions defined as patients admitted with a Trauma Surge Index (TSI) ≤3, and high-surge admissions defined as patients admitted with a TSI >3.

[†] Chi-square used to calculate p value for categorical variables and *t*-test used to calculate p value for continuous variables.

ISS, Injury Severity Score.

and the hospital-day level, increasing the estimated SEs. We used posterior prediction models to determine probability of risk-adjusted mortality at each surge level.

Once the probability of risk-adjusted mortality was calculated at each surge level, an increased probability of mortality was observed at TSI levels >3. Based on that observation, we dichotomized the TSI surge measure to define high (TSI >3) and low (TSI ≤3) surge periods, empirically deriving a definition of high-surge period. Frequencies of high-surge days and patients exposed to high-surge days were calculated, and then we performed clustered multivariable logistic regression with the dichotomized TSI surge measure as an independent variable and mortality as the dependent variable. All patients were included in these analyses using the dichotomous TSI measure (≤3 and >3).

Table 2. Distribution of Patients (n = 230,621) and Hospital Days (n = 110,230) per Surge Level

	All hospitals		Low volume (tertile 1)		Medium volume (tertile 2)		High volume (tertile 3)	
Surge type	**Patients, %**	**Days, %**	**Patients, %**	**Days, %**	**Patients, %**	**Days, %**	**Patients, %**	**Days, %**
Mass casualty event*	13.23	3.87	0.80	0.19	3.28	1.17	21.89	10.32
Trauma Surge Index†								
≤0	86.10	85.98	77.76	80.30	86.56	88.02	88.16	87.76
1	11.50	11.34	16.31	14.27	11.44	10.17	10.20	10.53
2	1.94	2.05	3.90	3.49	1.83	1.64	1.46	1.49
3	0.32	0.41	1.15	1.08	0.17	0.15	0.17	0.21
4	0.07	0.11	0.38	0.41	0.01	0.02	0.01	0.01
5	0.03	0.05	0.20	0.20	‡	‡	‡	‡
6	0.02	0.03	0.13	0.12	‡	‡	‡	‡
7	0.01	0.02	0.07	0.06	‡	‡	‡	‡
≥8	0.02	0.01	0.10	0.08	‡	‡	‡	‡

*Defined as 10 patients admitted within 24 hours or at least 3 patients with Injury Severity Scores >15 within 3 hours.

†Defined as difference between aggregate injury severity score of patients (−24 hours/+24 hours) and annual median aggregated injury severity score per hospital day, divided by annual median aggregated interquartile range per hospital day.

‡Trauma Surge Index surge level not observed in these hospitals.

Next, we sought to determine if certain patient populations were particularly impacted by trauma surges. Limited evidence suggests that patients with firearms injuries have had increased mortality during trauma surges, so we tested for an interaction effect between mechanism of injury and the 2 surge measures (MCE and dichotomized TSI) in separate regression models.[6] A significant interaction was noted between the TSI variable and firearm injuries, so we used a posterior predictive model to calculate risk of mortality during high- and low-surge periods for patients with firearm injury and nonfirearm injury.

To determine if hospital trauma admission volume impacted mortality associated with trauma surges, we stratified patients by hospital annual trauma admission volume divided into tertiles (low, medium, and high volume), and we performed clustered multivariable logistic regression with each surge measure. Also, we tested for 2-way interaction between tertile of annual trauma admission volume and each surge measure (MCE and dichotomized TSI).

Finally, we performed several additional analyses to test the robustness of our findings. When we constructed the TSI a priori, we defined a surge period as 48 hours, 24 hours before and 24 hours after hospital admission. To examine the validity of that definition, we performed sensitivity analysis by calculating the TSI using several alternative definitions of a surge period (12, 24, 60, and 72 hours). Using each alternative TSI measure, we performed multivariable logistic regression to examine the TSI surge to mortality relationship. For each surge duration, we also performed sensitivity analysis by adjusting the threshold of a high-surge period to TSI >1 and TSI >2, and we used those alternative definitions in mortality models to examine the surge-mortality relationship.

Finally, we performed several additional tests to evaluate the validity of our regression model using the initial, empirically derived definition of high TSI surge period (TSI >3 in a 48-hour surge period). First, we tested the area under the receiver operating characteristic (ROC) curve. Next, we performed 5-fold internal cross validation, testing the area under the ROC curve. Finally, we performed a Hosmer-Lemeshow goodness-of-fit test across 10 quantiles.

RESULTS

A total of 233,623 patients were admitted to 156 hospitals during the study period. Of those patients, 2,627 patients were excluded because they arrived without signs of life. An additional 375 patients were excluded because data on date and time of emergency department admission were lacking, leaving a total of 230,621 patients in the final study cohort (Table 1). The annual distribution of daily trauma admissions showed considerable variation between hospitals with many low-volume hospitals displaying a non-normal, highly skewed distribution. Table 2 summarizes the distribution of patients and hospital days by surge level using MCE and TSI criteria.

Overall in-hospital mortality in the patient cohort was 6.3%. Table 3 and Figure 1 display the relationship between surge level and risk-adjusted mortality. In the regression model using TSI as an integer value, a total of 46 patients at TSI levels 7, 9, 10, and 12 were not included

Table 3. Inpatient Mortality per Trauma Surge Index Level by Hospital Volume (n = 230,621)

	All hospitals, mortality		Low volume (tertile 1), mortality		Medium volume (tertile 2), mortality		High volume (tertile 3), mortality	
Surge type	**%**	**95% CI**	**%**	**95% CI**	**%**	**95% CI**	**%**	**95% CI**
Non-MCE*	6.3	6.1–6.6	6.2	5.5–7.0	6.4	6.0–6.8	6.3	6.0–6.5
MCE*	6.2	5.9–6.5	7.2	4.8–9.7	7.1	5.8–8.4	6.2	5.9–6.5
TSI†								
≤0	6.3	6.1–6.5	6.3	5.5–7.1	6.5	6.1–6.9	6.3	6.1–6.5
1	6.2	5.9–6.5	6.1	5.3–7.0	6.3	5.8–6.9	6.1	5.7–6.5
2	6.1	5.5–6.7	5.6	4.6–6.6	6.5	5.5–7.6	6.0	5.2–6.9
3	6.2	4.4–8.1	6.5	4.0–9.0	5.6	0.0–10.6	5.7	3.2–8.3
4	10.3	6.4–14.3	8.9	4.8–13.1	14.1	1.6–26.7	16.4	7.1–25.7
5	11.7	5.8–17.6	11.0	4.8–17.3	‡	—	‡	—
6	10.7	6.0–15.4	10.6	6.1–15.1	‡	—	‡	—
8	14.7	7.9–28.6	14.1	0.0–28.1	‡	—	‡	—

*Mass casualty event defined as 10 patients admitted within 24 hours or at least 3 patients with Injury Severity Scores >15 within 3 hours.

†Trauma Surge Index defined as difference between aggregate Injury Severity Score of patients (−24 hours/+24 hours) and annual median aggregated Injury Severity Score per hospital day, divided by annual median aggregated interquartile range per hospital day.

‡Trauma Surge Index surge level not observed in these hospitals.

MCE, mass casualty event; TSI, Trauma Surge Index.

in the analysis due to the small number of observations and lack of variation in outcomes at those TSI levels. A significant increase in mortality was observed among patients with a TSI >3 when compared with patients with a TSI ≤3 (odds ratio [OR] = 2.05; 95% CI, 1.36–3.10); however, no difference in mortality was observed between MCE and non-MCE periods (OR = 0.94; 95% CI 0.88–1.01). Patients admitted under low-surge (TSI ≤3) conditions showed a predicted mortality of 6.3%, which increased to 9.9% during high-surge (TSI >3) periods. We observed a trend for patients admitted under high-surge conditions to display higher Glasgow Coma Scale motor scores, and these patients were less likely to have been transferred from another institution (Table 1). A total of 332 patients (0.14%) from the entire cohort exhibited a TSI score >3, and those patient admissions occurred on 172 days in 33 different hospitals.

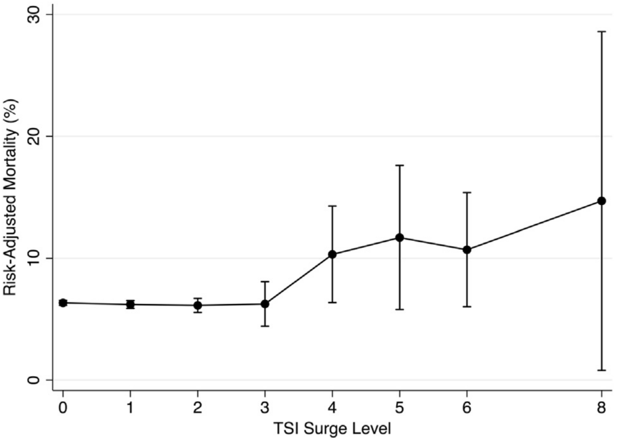

Figure 1. Risk-adjusted mortality per Trauma Surge Index (TSI) surge level with 95% CI, all patients (n = 230,621).

The influence of high-surge conditions on mortality was particularly pronounced among patients with firearms injuries (Figure 2). For those patients, probability of mortality increased from 15.5% during low-surge periods to 42.0% during high-surge periods. In contrast, the probability of mortality among nonfirearm patients increased from 5.8% during low-surge periods to 8.5% during high-surge periods. For both cohorts, patients with firearm and nonfirearm injuries, the increased mortality associated with high-surge periods was significant at p = 0.002 and p = 0.004, respectively. Evidence of the TSI surge-mortality relationship was observed in all hospital types by trauma admission volume (low-, medium-, and high-volume), but only reached statistical significance in low- and high-volume hospitals.

During the sensitivity analyses, when we changed the duration of the surge period from 48 hours to 12 hours, patients exposed to high-surge periods (TSI >3) had no significantly increased mortality compared with low-surge periods (OR = 1.20; 95% CI, 0.93–1.56). We found modest, yet significant increases in mortality when we set the surge period at 24 hours (OR = 1.51; 95% CI, 1.01–2.27). Mortality attributable to the high-surge period peaked when the surge duration was defined as 60 hours (OR = 2.37; 95% CI, 1.60–3.48). At 72 hours, however, high-surge periods were no longer

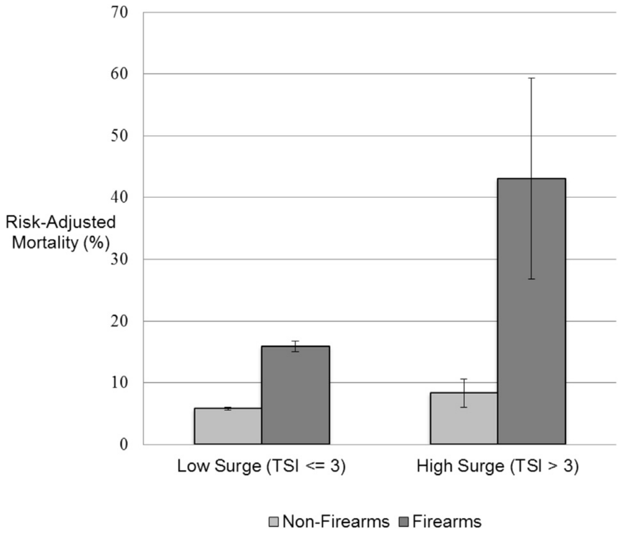

Figure 2. Risk-adjusted mortality for patients with firearm injuries and nonfirearm injuries using Trauma Surge Index (TSI) with 95% CIs.

associated with significantly increased risk (OR = 1.24; 95% CI, 0.76—2.01). Of note, lowering the threshold of a high-surge period to TSI >1 produced no significant mortality increase at any surge duration. However, with a surge period of 60 hours, mortality during high-surge periods defined as TSI >2 remained significantly elevated (OR = 1.49; 95% CI 1.02—2.16), and 816 patients (0.35% of the total cohort) were exposed to those surge conditions. Results of the sensitivity analyses are detailed in Table 4.

Finally, the area under the ROC curve was 0.91, and the result of the 5-fold internal cross validation using the area under the ROC curve was 0.90. The results of the Hosmer-Lemeshow test demonstrated better goodness-of-fit among high-risk patients than low-risk patients. In the lowest-risk quantile, the observed to expected ratio for mortality was only 0.51. However, the ratio consistently increased in higher risk cohorts, and the highest-risk quantile had an observed to expected ratio of 1.00.

DISCUSSION

Recent policy directives emphasize hospital surge capacity during MCEs, and such recent events as the bombing in Boston underscore the importance of the issue as well.[17] However, our ability to assess surge capacity is limited by the current methods used to measure capacity strain at both the hospital level and the system level. Previously used measures of capacity strain do not examine patient-level factors, such as injury severity; therefore, these measures do not distinguish the resources required to treat minimal injuries from those needed to treat devastating wounds. In addition, earlier measures hold all hospitals to a single standard and do not account for hospital-level variations in resource capacity. In this study, we sought to address these shortcomings by developing an improved measure of capacity strain. We developed a measure that can be used to examine trauma surges retrospectively and assess the necessary resources to improve trauma preparedness and response at single institutions and across communities.

First, we compared our novel measure of capacity strain, the TSI, with MCE criteria to analyze trauma surges that occurred during a 2-year period using both definitions. To assess each measure, we examined the relationship between trauma surge period and inpatient trauma mortality, the most relevant signal of hospital strain. We found that hospital conditions during which trauma patients were admitted varied greatly, and hospitals were remarkably resilient to surge capacity strain overall. However, periods of exceptionally high surge capacity strain, clear statistical outliers, were associated with increased inpatient trauma mortality. Importantly, these overwhelming surges were identified by the TSI, but not by MCE criteria. In addition, they occurred in our hospital cohort, on average, at least once per week.

Notably, the number of patients found to constitute an overwhelming trauma surge varied greatly between hospitals. This variation was dependent on the typical patient acuity and trauma admission volume of the hospital. For example, a patient was exposed to a surge that consisted of only 3 other severely injured trauma patients in a low-volume hospital (138 annual trauma admissions), and another patient was exposed to a surge that consisted of 20 trauma patients in a high-volume hospital (1,403 annual trauma admissions). The TSI of these patients was 5 and 4 respectively, and an increased risk of mortality was observed when compared with similar patients admitted to these hospitals during low-surge periods. These findings underscore that the impact of smaller-scale surges in low-volume hospitals is likely to be underappreciated as a matter of public health.

Next, we found that patients with firearms injuries were particularly vulnerable during trauma surges. Although it is unclear precisely why trauma surges affected those patients so dramatically, the treatment of firearms injuries is often resource intensive, requiring early surgical intervention and intensive care. Therefore, patient care might have become compromised as hospital resources became constrained. Again, we found no evidence that use of the MCE definition of trauma surge detected a difference

Table 4. Mortality and Number of Patients Included when Defining the Trauma Surge Index Using Alternative Surge Period Durations and Alternative Trauma Surge Index Levels to Define High-Surge Periods

High-surge period definition	Surge period duration				
	12 h	**24 h**	**48 h**	**60 h**	**72 h**
TSI >3					
Mortality, OR	1.20	1.51	2.05	2.37	1.24
95% CI	0.93–1.56	1.01–2.27	1.36–3.10	1.61–3.48	0.76–2.01
Patients, n (%)	1,552 (0.67)	661 (0.29)	332 (0.14)	293 (0.13)	248 (0.11)
TSI >2					
Mortality, OR	1.13	1.15	1.28	1.49	1.64
95% CI	0.96–1.34	0.93–1.42	0.89–1.86	1.02–2.16	1.12–2.44
Patients, n (%)	3,871 (1.68)	2,181 (0.95)	1,071 (0.46)	816 (0.35)	690 (0.30)
TSI >1					
Mortality, OR	1.04	1.05	1.01	1.00	1.04
95% CI	0.94–1.15	0.93–1.18	0.87–1.16	0.85–1.18	0.87–1.25
Patients, n (%)	11,876 (5.15)	8,348 (3.62)	5,542 (2.40)	4,658 (2.02)	4,163 (1.81)

OR, odds ratio; TSI, Trauma Surge Index.

in trauma patient mortality. This negative finding underscores the importance of controlling for patient acuity and the admission patterns of individual hospitals when evaluating trauma surge capacity.

The current study represents a novel use of currently available clinical registry data to estimate both the health care needs of trauma patients and hospital resource availability, but it measures neither factor directly. Although the ISS is a well-validated predictor of patient mortality, the precise relationship between ISS and resource use is unclear.[22-25] Empirical measurement of factors, such as the number of patients who require an operative procedure or mechanical ventilation, could provide a more direct measure of resource use. However, because capacity strain is likely a function of both resource use and availability (such as the number of operating rooms and ventilators available at any given time), an empirical analysis of surge capacity strain would require real-time data on resource availability at specific hospitals. In addition, trauma registry data do not include laboratory results, such as base deficit and serum lactate, more specific measures of tissue ischemia than systolic blood pressure, one of the variables used in this study to risk-stratify the patient population.[26] To better quantify the resuscitation needs of each patient, future studies should include such laboratory data. Currently, these more complex analyses, however, are only feasible for individual hospitals, and such detailed hospital-level and patient-level data are not available to examine a broad range of hospitals.[5]

Although our findings are compelling, this study has some limitations. We developed the TSI in an a priori manner, specifically to detect statistically rare events, so it is not surprising that so few patients (0.14% of the entire patient population) were exposed to high-surge periods (TSI >3). However, the decision to use a TSI >3 to define a high-surge period was derived empirically, based on the results of the initial mortality analysis. Arriving at the definition in this fashion increases the possibility of model overfitting. Although our results demonstrate the mortality model has robust internal validity, the TSI will still require additional validation using other datasets. Future studies should also validate the duration of time used to define a TSI surge period because the results of our sensitivity analyses suggest that a 48-hour period might result in an underestimation of both the mortality effect and number of people affected by trauma surges. Another limitation of this study is that we only sought to measure capacity strain among trauma patients. Therefore, we did not assess the potential impact of capacity strain produced by nontrauma patients, and did we not examine the potential impact of trauma surges on nontrauma patients.

To examine the influence of nontrauma patients, future studies will need robust clinical and hospital census data that include actual date and time of hospital admissions, procedures, and discharges, as well as nursing ratios and operating room availability. With that additional information, it would be feasible to examine the relationship between the TSI and other measures of hospital capacity strain, such as nursing shortages, overall bed capacity, and the National Emergency Department Overcrowding Score.[27-29] Additionally, the TSI surge-mortality model produced increasingly large SEs at TSI surge levels that represented statistical outliers. However, with increased observations at those surge levels during a longer period of time, the SEs should decrease, and the TSI should provide a more reliable estimation of the clinical consequence of surge capacity strain. Finally, we recognize that implementation of the TSI for real-time trauma surge response is not feasible due to both delays in the calculation of the ISS and the complexity of the measure.

In its current form, the TSI is most appropriate for retrospective analyses of surge response capacity and subsequent root cause analyses of associated increased mortality in trauma patients. Although TSI shows advantages over MCE, additional research is needed to validate the TSI. Future studies should use the event study method, well described in economics literature, to examine variation in hospital performance under surge conditions, and identify factors that account for such variation.[30] Those studies should focus on the use of critical resources, such as ventilators, operating rooms, available beds, and staffing during periods of high-capacity strain identified by the TSI; identify potential methods to recruit additional resources when needed; and examine how resource availability is communicated to prehospital providers and other hospitals within a region. We are hopeful that future studies not only examine resources and practices needed to improve trauma preparedness and response, but also identify protective attributes of high-performing hospitals and trauma systems. Thereby, novel applications of TSI can help shape trauma surge preparedness and response as an emerging quality metric.

CONCLUSIONS

In summary, the current study demonstrates a novel measure of hospital capacity strain attributable to the admission of trauma patients, the TSI. The TSI can be effectively applied to measure trauma surge capability across a broad range of hospitals and to examine the impact of hospital capacity strain on trauma patient mortality. Interestingly, we identified a specific population—patients with firearms injuries—that appears to be particularly vulnerable during trauma surges using TSI.

To our knowledge, this study represents the first attempt to quantify trauma surges that have occurred in hospitals across North America. Hospital performance during trauma surges appears to depend on patient acuity, mechanism of injury, and volume, as well as individual hospital trauma admission patterns. Stakeholders involved in trauma system preparedness and response can use the TSI to examine surge response capacity retrospectively and allocate scarce health care resources in an evidence-based manner. The TSI might be particularly useful in a global context in which many trauma systems are in their nascence.

Author Contributions

Study conception and design: Jenkins, Richardson, Norton, Cooke, Nathens, Hemmila
Acquisition of data: Jenkins, Nathens, Hemmila
Analysis and interpretation of data: Jenkins, Richardson, Norton, Cooke, Banerjee
Drafting of manuscript: Jenkins, Richardson, Norton, Cooke, Banerjee, Nathens, Hemmila
Critical revision: Jenkins, Richardson, Norton, Cooke, Banerjee, Nathens, Hemmila

REFERENCES

1. Mathers C, Fat DM, Boerma JT, et al. The Global Burden of Disease: 2004 Update. Geneva, Switzerland: World Health Organization; 2008. vii, 146.
2. Abir M, Choi H, Cooke CR, et al. Effect of a mass casualty incident: clinical outcomes and hospital charges for casualty patients versus concurrent inpatients. Acad Emerg Med 2012;19:280–286.
3. Ball CG, Kirkpatrick AW, Mulloy RH, et al. The impact of multiple casualty incidents on clinical outcomes. J Trauma 2006;61:1036–1039.
4. Frykberg ER, Tepas JJ 3rd. Terrorist bombings. Lessons learned from Belfast to Beirut. Ann Surg 1988;208:569–576.
5. Hirshberg A, Scott BG, Granchi T, et al. How does casualty load affect trauma care in urban bombing incidents? A Quantitative analysis. J Trauma 2005;58:686–695.
6. Peleg K, Rozenfeld M, Stein M. Poorer outcomes for mass casualty events victims: is it evidence based? J Trauma Acute Care Surg 2010;69:653–659.
7. Peleg K, Kellermann AL. Enhancing hospital surge capacity for mass casualty events. JAMA 2009;302:565–567.
8. Beilman GJ, Taylor JH, Job L, et al. Population-based prediction of trauma volumes at a Level 1 trauma centre. Injury 2004;35:1239–1247.
9. Mathers CD, Loncar D. Projections of global mortality and burden of disease from 2002 to 2030. PLoS Med 2006;3:e442.
10. Angus DC, Kelley MA, Schmitz RJ, et al. Caring for the critically ill patient. Current and projected workforce requirements for care of the critically ill and patients with pulmonary disease: can we meet the requirements of an aging population? JAMA 2000;284:2762–2770.
11. Cooper RA. Weighing the evidence for expanding physician supply. Ann Intern Med 2004;141:705–714.
12. Howell MD. Managing ICU throughput and understanding ICU census. Curr Opin Crit Care 2011;17:626–633.
13. Wagner J, Gabler NB, Ratcliffe SJ, et al. Outcomes among patients discharged from busy intensive care units. Ann Intern Med 2013;159:447–455.
14. Halpern SD. ICU capacity strain and the quality and allocation of critical care. Curr Opin Crit Care 2011;17:648–657.
15. Kaji A, Koenig KL, Bey T. Surge capacity for healthcare systems: a conceptual framework. Acad Emerg Med 2006;13: 1157–1159.
16. Watson SK, Rudge JW, Coker R. Health systems' "surge capacity": state of the art and priorities for future research. Milbank Q 2013;91:78–122.
17. Assistant Secretary for Preparedness and Response. Hospital Preparedness Program (HPP) Measure Manual:

Implementation Guidance for the HPP Program Measures. Available at: http://www.phe.gov/Preparedness/planning/evaluation/Documents/hpp-bp2-measuresguide-2013.pdf. Accessed July 31, 2014.

18. American College of Surgeons Committee on Trauma. Advanced Trauma Life Support for Doctors. Chicago, IL: American College of Surgeons; 2008:321—336.
19. Newgard CD, Fildes JJ, Wu L, et al. Methodology and analytic rationale for the American College of Surgeons Trauma Quality Improvement Program. J Am Coll Surg 2013;216:147—157.
20. American College of Surgeons Trauma Quality Improvement Program. ACS TQIP benchmark report: 2011 admissions. Chicago, IL: American College of Surgeons 2012.
21. Rubinson L, Mutter R, Viboud C, et al. Impact of the fall 2009 influenza A(H1N1)pdm09 pandemic on US Hospitals. Med Care 2013;51:259—265.
22. Rowell SE, Barbosa RR, Diggs BS, et al. Specific abbreviated injury scale values are responsible for the underestimation of mortality in penetrating trauma patients by the injury severity score. J Trauma 2011;71[Suppl 3]:S384—S388.
23. Glance LG, Osler TM, Mukamel DB, et al. Expert consensus vs empirical estimation of injury severity: effect on quality measurement in trauma. Arch Surg 2009;144:326—332; discussion 332.
24. Husum H, Strada G. Injury severity score versus new injury severity score for penetrating injuries. Prehosp Disaster Med 2002;17:27—32.
25. Bolorunduro OB, Villegas C, Oyetunji TA, et al. Validating the Injury Severity Score (ISS) in different populations: ISS predicts mortality better among Hispanics and females. J Surg Res 2011;166:40—44.
26. Tisherman SA, Barie P, Bokhari F, et al. Clinical practice guideline: endpoints of resuscitation. J Trauma 2004;57:898—912.
27. Hoot NR, Zhou C, Jones I, et al. Measuring and forecasting emergency department crowding in real time. Ann Emerg Med 2007;49:747—755.
28. Weiss SJ, Ernst AA, Sills MR, et al. Development of a novel measure of overcrowding in a pediatric emergency department. Pediatr Emerg Care 2007;23:641—645.
29. Schilling PL, Campbell DA Jr, Englesbe MJ, et al. A comparison of in-hospital mortality risk conferred by high hospital occupancy, differences in nurse staffing levels, weekend admission, and seasonal influenza. Med Care 2010;48:224—232.
30. MacKinlay AC. Event studies in economics and finance. J Econ Lit 1997;35:13—39.

APPENDIX 1. FORMULAS FOR TRAUMA SURGE LOAD AND TRAUMA SURGE INDEX

$$\textit{Trauma Surge Load } (TSL)_{Patient\ i} = \sum_{i=0}^{i+24hours} ISS + \sum_{i=0}^{i-24\ hours} ISS, \text{ where}$$

$\sum_{i=0}^{i+24hours} ISS$ represents the sum of Injury Severity Scores of patients admitted up to 24-hours after the admission of Patient$_i$; and $\sum_{i=0}^{i-24\ hours} ISS$ represents the sum of Injury Severity Scores of patients admitted up to 24-hours prior to the admission of Patient$_i$.

$$\textit{Trauma Surge Index } (TSI)_{Patient\ i} = \frac{TSL_{Patient\ i} - \widetilde{TSL}_{Hospital,\ Year}}{TSL\left(Q_3 - Q_1\right)_{Hospital,\ Year}}, \text{ where}$$

$\widetilde{TSL}_{Hospital,\ Year}$ represents the median annual Trauma Surge Load at the hospital to which the patient was admitted; and $TSL\left(Q_3 - Q_1\right)_{Hospital,\ Year}$ represents annual Trauma Surge Load interquartile range, 75th percentile minus 50th percentile, at the hospital to which the patient was admitted.