Hospital volume-outcome relationship in severe traumatic brain injury: stratified analysis by level of trauma center

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OBJECTIVE The nature of the volume-outcome relationship in cases with severe traumatic brain injury (TBI) remains unclear, with considerable interhospital variation in patient outcomes. The objective of this study was to understand the state of the volume-outcome relationship at different levels of trauma centers in the United States.

METHODS The authors queried the National Trauma Data Bank for the years 2007–2014 for patients with severe TBI. Case volumes for each level of trauma center organized into quintiles (Q1–Q5) served as the primary predictor. Analyzed outcomes included in-hospital mortality, total hospital length of stay (LOS), and intensive care unit (ICU) stay. Multivariable regression models were performed for in-hospital mortality, overall complications, and total hospital and ICU LOSs to adjust for possible confounders. The analysis was stratified by level designation of the trauma center. Statistical significance was established at $p < 0.001$ to avoid a type I error due to a large sample size.

RESULTS A total of 122,445 patients were included. Adjusted analysis did not demonstrate a significant relationship between increasing hospital volume of severe TBI cases and in-hospital mortality, complications, and nonhome hospital discharge disposition among level I–IV trauma centers. However, among level II trauma centers, hospital LOS was longer for the highest volume quintile (adjusted mean difference [MD] for Q5: 2.83 days, 95% CI 1.40–4.26 days, $p < 0.001$, reference = Q1). For level III and IV trauma centers, both hospital LOS and ICU LOS were longer for the highest volume quintile (adjusted MD for Q5: LOS 4.6 days, 95% CI 2.3–7.0 days, $p < 0.001$; ICU LOS 3.2 days, 95% CI 1.6–4.8 days, $p < 0.001$).

CONCLUSIONS Higher volumes of severe TBI cases at a lower level of trauma center may be associated with a longer LOS. These results may assist policymakers with target interventions for resource allocation and point to the need for careful prehospital decision-making in patients with severe TBI.

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KEYWORDS traumatic brain injury; head trauma; surgery; hospital volume; outcome analysis; volume-outcome relationship; National Trauma Data Bank; mortality; length of stay; ICU days

THE volume-outcome relationship in trauma centers has been a subject of debate in the last 2 decades. Conflicting analyses have demonstrated that a higher case volume is associated with improved outcomes^{5,10,12,14,16,22} or is not associated with any overall effect.^{3,7,9,11,17} The American College of Surgeons (ACS) has developed guidelines outlining minimum volume standards for level I and level II trauma centers.² For example, according to the ACS, level I trauma centers are required

to admit at least 1200 trauma patients yearly or to have 240 admissions with an Injury Severity Score (ISS) of more than 15. Larger volumes of patients provide the trauma team with more experience that should result in improved outcomes.¹⁵ A minimum volume is needed for experience, but at a certain point, overloading trauma center resources with minimally injured patients may diminish their effectiveness.¹³

Although many surgical subspecialties have demon-

ABBREVIATIONS ACS = American College of Surgeons; AIS = Abbreviated Injury Scale; GCS = Glasgow Coma Scale; ICP = intracranial pressure; ICU = intensive care unit; ISS = Injury Severity Score; LOS = length of stay; MD = mean difference; NTDB = National Trauma Data Bank; TBI = traumatic brain injury.

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strated the volume-outcome relationship among several elective procedures, such as endocrine, vascular, cardiac, gastrointestinal, and urological procedures, the nature of this relationship in traumatic brain injury (TBI) cases remains unclear, with considerable interhospital variation in patient outcomes.^{5,7,9,10,12,14,16–18,22} Some studies have demonstrated no significant relationship, while others have found a significant impact of hospital volume on outcomes in TBI.^{1,21} Inconsistent results from these studies may be attributable to differing statistical analyses, source populations, databases, or geographic variations.^{1,20,21} To address this knowledge gap, we queried a national trauma registry to understand the state of the volume-outcome relationship at different levels of trauma centers in the United States.

Methods

Data Source and Patient Population

This cohort study was conducted to analyze the hospital volume-outcome relationship in TBI. We queried the National Trauma Data Bank (NTDB) for the years 2007–2014 for adult patients (age ≥ 18 years) with an admission diagnosis of severe TBI, defined as Glasgow Coma Scale (GCS) score ≤ 8 , and an Abbreviated Injury Scale (AIS) head score ≥ 3 . We excluded nonsurvival TBI with an AIS head score of 6, dead on arrival, and penetrating TBI. The NTDB contains information on hospital characteristics, patient demographics, prehospital care, diagnoses, injury severity scoring, inpatient care, complications, as well as outcomes. The NTDB is the largest aggregation of trauma registry data ever assembled.

Variables

The primary predictor was defined as the annual volume (organized into quintiles: Q1–Q5) of severe TBI cases at the hospital (calculated separately for each designated level of trauma center). Patient-level covariates of interest included demographics such as age, sex, and race; insurance status; comorbidities; type of surgical intervention (burr hole, craniectomy, and removal of hematoma); type of intracranial pathology (epidural, subdural, brainstem, and cerebellar hematomas); GCS score; hypotension on admission (defined as systolic blood pressure < 90 mm Hg); ISS score; and complications. The primary outcome evaluated was in-hospital mortality. Secondary outcomes included 1) overall complications (acute kidney injury, acute respiratory distress syndrome, cardiac arrest, catheter-associated urinary tract infection, central line-associated bloodstream infection, deep surgical site infection, deep vein thrombosis, pulmonary embolism, myocardial infarction, organ/space surgical site infection, pressure ulcer, severe sepsis, stroke, superficial incisional surgical site infection, unplanned admission to the intensive care unit [ICU], ventilator-associated pneumonia, or unplanned return to the operating room), 2) total hospital length of stay (LOS), 3) ICU stay, and 4) nonhome discharge. The ICD-9-CM procedural codes for adjusting the outcome included craniectomy (01.23, 01.25, 01.26, 01.39, 01.51, and 02.01), burr hole (01.09), removal of epidural hematoma (01.24), removal of subdural hematoma (01.31),

removal of intracerebral hematoma (01.39), and intracranial pressure (ICP) monitoring (01.10). The type of intracranial pathology was defined using ICD-9-CM diagnosis codes: epidural hematoma (852.4), subdural hematoma (852.2 and 852.3), and intracerebral lesions (851.4, 851.5, 851.6, 851.7, 852.0, and 852.1).

Statistical Analysis

All statistical analyses were performed using Stata/MP statistical software version 14.2 (1985–2015, StataCorp LLC). Descriptive statistics were computed for patient-level and hospital-level characteristics. Categorical and continuous variables were compared using chi-square and two-sample t-tests. A multilevel mixed-effects logistic regression model was used to evaluate in-hospital mortality. Similarly, a mixed-effects linear regression was fitted for total hospital LOS and ICU stay (days) with hospital volume of severe TBI cases as the primary predictor. To account for hospital-level covariates, hospital characteristics such as number of beds and teaching status were added as covariates, while the results were clustered for reporting facility. Some authors have suggested that multilevel modeling should be considered to evaluate in-hospital mortality in trauma patients.⁴ Both regression models were adjusted for the following variables: age, sex, race, insurance, hypotension on admission (systolic blood pressure < 90 mm Hg), ISS score, preadmission interhospital transfer, GCS score on admission, comorbidities (hypertension, diabetes, cerebrovascular accident, hemodialysis, and cancer with chemotherapy), intracranial lesions (epidural, subdural, brainstem, and cerebellar hematomas), utilization of ICP monitoring, and procedure performed (burr hole and craniectomy). Adjustments were based on the guidelines reported in the article by Haider et al.⁸ The analysis was stratified by level of trauma center. Adjusted odds ratios and coefficients with 95% confidence intervals were calculated from the logistic regression analysis. For LOS, the outcome of interest was the adjusted mean difference (MD; in days) along with 95% confidence intervals. The p values were two-sided, and statistical significance was established at $p \leq 0.001$ (because of the large sample size).

Results

Study Population

Between 2007 and 2014, a total of 5,836,508 patients were registered in the NTDB data set. After applying our inclusion and exclusion criteria, 77,592 subjects with severe TBI were eligible for analysis. Among level I trauma centers, low- to high-volume quintiles were identified as ≤ 357 , 358–482, 483–642, 643–765, and ≥ 766 cases of severe TBI annually. For level II trauma centers, volume quintiles of severe TBI (low to high) were identified as ≤ 121 , 122–189, 190–240, 241–322, and ≥ 323 cases/year. Tables 1 and 2 summarize the patient-level and hospital-level characteristics of level I and level II trauma centers by volume. The proportion of the Hispanic population showed an increasing trend from low- to high-volume hospitals (10.8% to 14.7%). As for the GCS score, however, more severe cases (GCS 3) appeared in higher-volume

TABLE 1. Patient and hospital characteristics in level I trauma centers

Variable	Low Volume (≤357 cases/yr)	Low-Medium Volume (358–482 cases/yr)	Medium Volume (483–642 cases/yr)	Medium-High Volume (643–765 cases/yr)	High Volume (≥766 cases/yr)	p Value
No. of patients	10,503	10,538	10,588	10,685	9666	
Median age in yrs (IQR)	48 (29–65)	47 (28–64)	44 (28–59)	45 (28–62)	45 (28–61)	
Male, no. (%)	7722 (73.52)	7627 (72.38)	7990 (75.46)	7886 (73.80)	7005 (72.47)	<0.001
Race, no. (%)						
White	7083 (67.44)	7636 (72.46)	6851 (64.71)	6813 (63.76)	7067 (73.11)	<0.001
Black	1158 (11.03)	703 (6.67)	1147 (10.83)	1143 (10.70)	854 (8.84)	
Hispanic	1035 (9.85)	1078 (10.23)	1253 (11.83)	1700 (15.91)	1412 (14.61)	
Other	700 (6.66)	703 (6.67)	860 (8.12)	640 (5.99)	299 (0.30)	
Unknown	527 (5.02)	418 (3.97)	477 (4.51)	389 (3.64)	34 (0.35)	
Comorbid illnesses, no. (%)						
Alcoholism	1373 (13.07)	1142 (10.84)	1607 (15.18)	1537 (14.38)	963 (9.96)	<0.001
Bleeding	539 (5.13)	590 (5.60)	447 (4.22)	550 (5.15)	519 (5.37)	<0.001
CVA	270 (2.57)	229 (2.17)	154 (1.45)	218 (2.04)	327 (3.38)	<0.001
COPD	440 (4.19)	307 (2.91)	350 (3.31)	394 (3.69)	363 (3.76)	<0.001
Chronic renal failure	70 (0.67)	55 (0.52)	74 (0.70)	71 (0.66)	55 (0.57)	0.44
Liver cirrhosis	44 (0.42)	50 (0.47)	63 (0.60)	103 (0.96)	45 (0.47)	<0.001
Chronic heart failure	208 (1.98)	228 (2.16)	171 (1.62)	237 (2.22)	196 (2.03)	0.017
Smoker	728 (6.93)	796 (7.55)	923 (8.72)	532 (4.98)	933 (9.65)	<0.001
Cancer w/ current chemotherapy	22 (0.21)	22 (0.21)	14 (0.13)	24 (0.22)	14 (0.14)	0.40
Dementia	65 (0.62)	48 (0.46)	66 (0.62)	93 (0.87)	69 (0.71)	0.005
Dependent status	73 (0.70)	96 (0.91)	84 (0.79)	101 (0.95)	49 (0.51)	0.002
Hypertension	2120 (20.18)	1923 (18.25)	1647 (15.56)	1883 (17.62)	1996 (20.65)	<0.001
Prematurity	1 (0.01)	3 (0.03)	0 (0.00)	4 (0.04)	2 (0.02)	0.30
Steroid	13 (0.12)	26 (0.25)	56 (0.53)	23 (0.22)	3 (0.03)	<0.001
Intracranial lesion, no. (%)						
EDH	677 (6.45)	571 (5.42)	636 (6.01)	482 (4.51)	541 (5.6)	<0.001
SDH	5390 (51.32)	4789 (45.45)	4450 (42.03)	4433 (41.49)	4612 (47.71)	<0.001
Traumatic SAH	115 (1.09)	109 (1.03)	95 (0.9)	48 (0.45)	70 (0.72)	<0.001
Brainstem/cerebellar lesion	369 (3.51)	247 (2.34)	296 (2.8)	326 (3.05)	180 (1.86)	<0.001
Surgical procedure, no. (%)						
Craniectomy	1933 (18.40)	1887 (17.91)	1834 (17.32)	1829 (17.12)	1539 (15.92)	<0.001
Burr hole	125 (1.19)	60 (0.57)	90 (0.85)	63 (0.59)	50 (0.52)	<0.001
Removal of EDH	954 (9.08)	878 (8.33)	980 (9.26)	935 (8.75)	766 (7.92)	0.01
Removal of SDH	1006 (9.58)	967 (9.18)	862 (8.14)	876 (8.20)	694 (7.18)	<0.001
Removal of ICH	164 (1.56)	208 (1.97)	199 (1.88)	170 (1.59)	122 (1.26)	0.001
ICP monitoring	675 (6.43)	681 (6.46)	515 (4.86)	322 (3.01)	621 (6.42)	<0.001

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TABLE 1. Patient and hospital characteristics in level I trauma centers

Variable	Low Volume (≤357 cases/yr)	Low-Medium Volume (358–482 cases/yr)	Medium Volume (483–642 cases/yr)	Medium-High Volume (643–765 cases/yr)	High Volume (≥766 cases/yr)	p Value
Insurance, no. (%)	7001 (66.66)	6932 (65.78)	7380 (69.70)	7017 (65.67)	6827 (70.63)	<0.001
Hypotension, no. (%)	1483 (14.12)	1398 (13.27)	1606 (15.17)	1458 (13.65)	1402 (14.50)	0.001
Cause of injury, no. (%)						
Fall	4099 (39.03)	3794 (36.0)	3168 (29.92)	3758 (35.17)	2947 (30.49)	<0.001
MVA	4885 (46.51)	5213 (49.47)	5814 (54.91)	5658 (52.95)	5382 (55.68)	
Pedestrian	223 (2.12)	170 (1.61)	171 (1.62)	151 (1.41)	106 (1.1)	
Struck by object	671 (6.39)	680 (6.45)	758 (7.16)	651 (6.09)	576 (5.96)	
Other	625 (5.95)	681 (6.46)	677 (6.39)	467 (4.37)	655 (6.78)	
ISS, no. (%)						
9–15	932 (8.87)	787 (7.47)	1212 (11.45)	619 (5.79)	667 (6.9)	<0.001
16–24	2421 (23.05)	2328 (22.09)	2416 (22.82)	2305 (21.57)	2176 (22.51)	
25–75	7044 (67.07)	7334 (69.60)	6872 (64.90)	7708 (72.14)	6777 (70.11)	
GCS score, no. (%)						
3	6943 (66.1)	8179 (77.61)	7982 (75.39)	7674 (71.82)	7513 (77.73)	<0.001
4–5	990 (9.43)	685 (6.50)	671 (6.34)	755 (7.07)	555 (5.74)	
6–8	2570 (24.47)	1674 (15.89)	1935 (18.28)	2256 (21.11)	1598 (16.53)	
Hospital status, no. (%)						
Community	3354 (31.93)	3075 (29.18)	1106 (10.45)	3248 (30.40)	0 (0)	<0.001
Nonteaching	203 (1.93)	85 (0.81)	0 (0)	0 (0)	0 (0)	
University	6946 (66.13)	7378 (70.01)	9482 (89.55)	7437 (69.60)	9666 (100)	
Bed size, no. (%)						
<200	3 (0.03)	187 (1.77)	453 (4.28)	0 (0)	99 (1.02)	<0.001
200–400	1443 (13.74)	1771 (16.81)	1724 (16.28)	158 (1.48)	0 (0)	
400–600	4092 (38.96)	5302 (50.31)	4383 (41.40)	1446 (13.53)	3173 (32.83)	
>600	4965 (47.27)	3278 (31.11)	4028 (38.04)	9081 (84.99)	6394 (66.15)	
No. of neurosurgeons	5	5	6	6	6	
No. of trauma surgeons	5	6	6	7	7	
Interhospital transfer, no. (%)						
No	7425 (70.69)	6321 (59.98)	6640 (62.71)	6945 (65.00)	6244 (64.60)	<0.001
Yes	3075 (29.28)	4179 (39.66)	3846 (36.32)	3682 (34.46)	3422 (35.40)	
Not known/not recorded	3 (0.03)	38 (0.36)	102 (0.96)	58 (0.54)	0 (0.00)	

COPD = chronic obstructive pulmonary disease; CVA = cerebrovascular accident; EDH = epidural hematoma; ICH = intracerebral hematoma; MVA = motor vehicle accident; SAH = subarachnoid hemorrhage; SDH = subdural hematoma.

Boldface type indicates statistical significance.

TABLE 2. Patient and hospital characteristics in level II trauma centers

Variable	Low Volume (≤121 cases/yr)	Low-Medium Volume (122–189 cases/yr)	Medium Volume (190–240 cases/yr)	Medium-High Volume (241–322 cases/yr)	High Volume (≥323 cases/yr)	p Value
No. of patients	4904	4795	5149	4701	4686	
Median age in yrs (IQR)	49 (29–67)	48 (29–65)	48 (29–64)	47 (29–65)	46 (29–62)	
Male, no. (%)	3472 (70.80)	3454 (72.03)	3734 (72.52)	3389 (72.09)	3413 (72.83)	0.131
Race, no. (%)						
White	3593 (73.27)	3337 (69.59)	3709 (72.03)	2950 (62.75)	3266 (69.70)	<0.001
Black	272 (5.55)	480 (10.01)	315 (6.12)	144 (3.06)	263 (5.61)	
Hispanic	358 (7.30)	412 (8.28)	618 (12.00)	501 (10.66)	749 (15.98)	
Other	420 (8.56)	284 (5.92)	357 (6.93)	524 (11.15)	232 (4.95)	
Unknown	261 (5.32)	282 (5.88)	150 (2.91)	582 (12.38)	176 (3.76)	
Comorbid illnesses, no. (%)						
Alcoholism	688 (14.03)	679 (14.16)	758 (14.72)	574 (12.21)	506 (10.80)	<0.001
Bleeding	297 (6.06)	318 (6.63)	306 (5.94)	369 (7.85)	227 (4.84)	<0.001
CVA	105 (2.14)	105 (2.19)	113 (2.19)	105 (2.23)	82 (1.75)	0.46
COPD	225 (4.59)	169 (3.52)	169 (3.28)	188 (4.00)	140 (2.99)	<0.001
Chronic renal failure	36 (0.73)	35 (0.73)	27 (0.52)	30 (0.64)	15 (0.32)	0.045
Liver cirrhosis	20 (0.41)	22 (0.46)	12 (0.23)	22 (0.47)	23 (0.49)	0.25
Chronic heart failure	120 (2.45)	113 (2.36)	108 (2.10)	119 (2.53)	76 (1.62)	0.019
Smoker	460 (9.38)	291 (6.07)	464 (9.01)	344 (7.32)	244 (5.21)	<0.001
Cancer w/ current chemotherapy	12 (0.24)	12 (0.25)	9 (0.17)	11 (0.23)	11 (0.23)	0.94
Dementia	39 (0.80)	33 (0.69)	36 (0.70)	21 (0.45)	13 (0.28)	0.005
Dependent status	49 (1.00)	40 (0.83)	31 (0.60)	30 (0.64)	27 (0.58)	0.065
Hypertension	1006 (20.51)	939 (19.58)	1023 (19.87)	1086 (23.10)	735 (15.69)	<0.001
Prematurity	1 (0.02)	0 (0.00)	2 (0.04)	0 (0.00)	1 (0.02)	0.52
Steroid	11 (0.22)	5 (0.10)	10 (0.19)	9 (0.19)	17 (0.36)	0.10
Intracranial pathology, no. (%)						
EDH	213 (4.34)	177 (3.69)	258 (5.01)	308 (6.55)	241 (5.14)	<0.001
SDH	2015 (41.09)	2061 (42.98)	2338 (45.41)	2543 (54.09)	2032 (43.36)	<0.001
Traumatic SAH	55 (1.12)	61 (1.27)	70 (1.36)	40 (0.85)	41 (0.87)	0.053
Brainstem/cerebellar lesion	77 (1.57)	110 (2.29)	130 (2.52)	135 (2.87)	102 (2.18)	<0.001
Surgical procedure, no. (%)						
Craniectomy	944 (19.25)	820 (17.10)	1060 (20.59)	892 (18.97)	897 (19.14)	0.001
Burr hole	47 (0.96)	45 (0.94)	30 (0.58)	68 (1.45)	41 (0.87)	0.001
Removal of EDH	433 (8.83)	409 (8.53)	565 (10.97)	584 (12.42)	509 (10.86)	<0.001
Removal of SDH	492 (10.03)	405 (8.45)	487 (9.46)	405 (8.62)	404 (8.62)	0.026
Removal of ICH	78 (1.59)	80 (1.67)	77 (1.50)	63 (1.34)	67 (1.43)	0.709
ICP monitoring	251 (5.12)	261 (5.44)	343 (6.66)	332 (7.06)	278 (5.93)	<0.001

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TABLE 2. Patient and hospital characteristics in level II trauma centers

Variable	Low Volume (≤121 cases/yr)	Low-Medium Volume (122–189 cases/yr)	Medium Volume (190–240 cases/yr)	Medium-High Volume (241–322 cases/yr)	High Volume (≥323 cases/yr)	p Value
Insurance, no. (%)	3612 (73.65)	3552 (74.08)	3962 (76.95)	3766 (80.11)	2937 (62.68)	<0.001
Hypotension, no. (%)	715 (14.58)	695 (14.49)	583 (11.32)	593 (12.61)	723 (15.43)	<0.001
Cause of injury, no. (%)						
Fall	2038 (41.56)	1749 (36.48)	1999 (38.82)	1794 (38.16)	1456 (31.07)	<0.001
MVA	2193 (44.72)	2347 (48.95)	2375 (46.13)	2097 (44.61)	2516 (53.69)	
Pedestrian	100 (2.04)	99 (2.06)	103 (2.00)	120 (2.55)	91 (1.94)	
Struck by object	247 (5.04)	276 (5.76)	308 (5.98)	298 (6.34)	292 (6.23)	
Other	326 (6.65)	324 (6.76)	364 (7.07)	392 (8.34)	331 (7.06)	
ISS, no. (%)						
9–15	443 (9.03)	355 (7.40)	530 (10.29)	365 (7.76)	411 (8.77)	<0.001
16–24	1101 (22.45)	1067 (22.25)	1205 (23.40)	1006 (21.40)	1018 (21.72)	
25–75	3306 (67.41)	3341 (69.68)	3371 (65.47)	3302 (70.24)	3227 (68.86)	
GCS score, no. (%)						
3	3150 (64.23)	3328 (69.41)	3809 (73.98)	3445 (73.28)	3586 (76.53)	<0.001
4–5	521 (10.62)	429 (8.95)	411 (7.98)	346 (7.36)	295 (6.30)	
6–8	1233 (25.14)	1038 (21.65)	929 (18.04)	910 (19.36)	805 (17.18)	
Hospital status, no. (%)						
Community	2686 (54.77)	3340 (69.66)	3843 (74.64)	2774 (59.01)	1669 (35.62)	<0.001
Nonteaching	1433 (29.22)	755 (15.75)	940 (18.26)	1127 (23.97)	1792 (38.24)	
University	785 (16.01)	700 (14.60)	366 (7.11)	800 (17.02)	1225 (26.14)	
Bed size, no. (%)						
<200	664 (13.54)	337 (7.03)	433 (8.41)	0 (0)	0 (0)	<0.001
200–400	3040 (61.99)	2191 (45.69)	1822 (35.39)	3547 (75.45)	1630 (34.78)	
400–600	1084 (22.10)	1570 (32.74)	1988 (38.61)	902 (19.19)	1742 (37.17)	
>600	116 (2.37)	697 (14.54)	906 (17.60)	252 (5.36)	1314 (28.04)	
No. of neurosurgeons	3	4	4	4	6	
No. of trauma surgeons	5	6	6	6	6	
Interhospital transfer, no. (%)						
No	3901 (79.55)	3403 (70.97)	3066 (59.55)	3448 (73.35)	3567 (76.12)	<0.001
Yes	1000 (20.39)	1366 (28.49)	2083 (40.45)	1253 (26.65)	1119 (23.88)	
Not known/not recorded	3 (0.06)	26 (0.54)	0 (0.00)	0 (0.00)	0 (0.00)	

Boldface type indicates statistical significance.

TABLE 3. Patient and hospital characteristics in level III and level IV trauma centers

Variable	Low Volume (≤16 cases/yr)	Low-Medium Volume (17–21 cases/yr)	Medium Volume (22–33 cases/yr)	Medium-High Volume (34–56 cases/yr)	High Volume (≥57 cases/yr)	p Value
No. of patients	285	300	309	229	254	
Median age in yrs (IQR)	57 (39–76)	54 (36–74)	49 (29–65)	47 (32–71)	51.5 (34–73)	
Male, no. (%)	193 (67.72)	203 (67.67)	237 (76.70)	152 (66.38)	165 (64.96)	0.048
Race, no. (%)						
White	220 (77.19)	240 (80.00)	226 (73.14)	198 (86.46)	156 (61.42)	<0.001
Black	28 (9.82)	26 (8.67)	5 (1.62)	18 (7.86)	6 (2.36)	
Hispanic	14 (4.91)	8 (2.67)	11 (3.56)	3 (1.31)	56 (22.05)	
Other	5 (1.75)	9 (3.00)	10 (3.24)	8 (3.49)	10 (3.94)	
Unknown	18 (6.32)	17 (5.67)	57 (18.45)	2 (0.87)	26 (10.24)	
Comorbid illnesses, no. (%)						
Alcoholism	34 (11.93)	33 (11.00)	31 (10.03)	16 (6.99)	32 (12.60)	0.30
Bleeding	13 (4.56)	14 (4.67)	18 (5.83)	16 (6.99)	14 (5.51)	0.75
CVA	15 (5.26)	9 (3.00)	2 (0.65)	5 (2.18)	1 (0.39)	<0.001
COPD	17 (5.96)	13 (4.33)	12 (3.88)	11 (4.80)	1 (0.39)	0.016
Chronic renal failure	1 (0.35)	1 (0.33)	0 (0.00)	2 (0.87)	1 (0.39)	0.59
Liver cirrhosis	0 (0.00)	1 (0.33)	0 (0.00)	1 (0.44)	0 (0.00)	0.51
Chronic heart failure	12 (4.21)	15 (5.00)	3 (0.97)	4 (1.75)	11 (4.33)	0.023
Smoker	11 (3.86)	6 (2.00)	19 (6.15)	18 (7.86)	8 (3.15)	0.008
Cancer w/ current chemotherapy	0 (0.00)	2 (0.67)	0 (0.00)	1 (0.44)	0 (0.00)	0.27
Dementia	3 (1.05)	2 (0.67)	4 (1.29)	3 (1.31)	1 (0.39)	0.77
Dependent status	4 (1.40)	6 (2.00)	3 (0.97)	1 (0.44)	1 (0.39)	0.32
Hypertension	60 (21.05)	76 (25.33)	53 (17.15)	51 (22.27)	53 (20.87)	0.18
Intracranial lesion, no. (%)						
EDH	13 (4.56)	8 (2.67)	18 (5.83)	9 (3.93)	7 (2.76)	0.254
SDH	130 (45.61)	133 (44.33)	135 (43.69)	103 (44.98)	98 (38.58)	0.507
Traumatic SAH	1 (0.35)	1 (0.33)	2 (0.65)	1 (0.44)	1 (0.39)	0.978
Brainstem/cerebellar lesion	3 (1.05)	2 (0.67)	4 (1.29)	4 (1.75)	1 (0.39)	0.592
Surgical procedure, no. (%)						
Craniectomy	8 (2.81)	22 (7.33)	34 (11.00)	12 (5.24)	41 (16.14)	<0.001
Burr hole	0 (0.00)	1 (0.33)	2 (0.65)	0 (0.00)	1 (0.39)	0.563
Removal of EDH	2 (0.70)	10 (3.33)	16 (5.18)	3 (1.31)	30 (11.81)	<0.001
Removal of SDH	7 (2.46)	11 (3.67)	15 (4.85)	8 (3.49)	6 (2.36)	0.455
Removal of ICH	1 (0.35)	4 (1.33)	3 (0.97)	2 (0.87)	8 (3.15)	0.054
ICP monitoring	0 (0.00)	8 (2.67)	2 (0.65)	3 (1.31)	12 (4.72)	<0.001
Insurance, no. (%)	222 (77.89)	215 (71.67)	186 (60.19)	183 (79.91)	209 (82.28)	0.002
Hypotension, no. (%)	41 (14.39)	33 (11.0)	47 (15.21)	30 (13.10)	34 (13.39)	0.579
Cause of injury, no. (%)						
Fall	153 (53.68)	152 (50.67)	146 (47.25)	89 (38.86)	126 (49.61)	<0.001
MVA	96 (33.68)	109 (36.33)	129 (41.75)	101 (44.10)	100 (39.37)	
Pedestrian	4 (1.40)	4 (1.33)	6 (1.94)	3 (1.31)	10 (3.94)	
Struck by object	20 (7.02)	18 (6)	13 (4.21)	19 (8.30)	6 (2.36)	
Other	12 (4.21)	17 (5.67)	15 (4.85)	17 (7.42)	12 (4.72)	
ISS, no. (%)						
9–15	45 (15.79)	40 (13.33)	51 (16.50)	24 (10.48)	3 (1.18)	<0.001
16–24	81 (28.42)	85 (28.33)	77 (24.92)	55 (24.02)	57 (22.44)	
25–75	154 (54.04)	170 (56.67)	173 (55.99)	147 (64.19)	192 (75.59)	

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TABLE 3. Patient and hospital characteristics in level III and level IV trauma centers

Variable	Low Volume (≤16 cases/yr)	Low-Medium Volume (17–21 cases/yr)	Medium Volume (22–33 cases/yr)	Medium-High Volume (34–56 cases/yr)	High Volume (≥57 cases/yr)	p Value
GCS score, no. (%)						
3	146 (51.23)	179 (59.67)	173 (55.99)	134 (58.52)	163 (64.17)	<0.001
4–5	37 (12.98)	38 (12.67)	39 (12.62)	20 (8.73)	34 (13.39)	
6–8	102 (35.79)	83 (27.67)	97 (31.39)	75 (32.75)	57 (22.44)	
Hospital status, no. (%)						
Community	82 (28.77)	81 (27.00)	96 (31.07)	95 (41.48)	73 (28.74)	<0.001
Nonteaching	153 (53.68)	190 (63.33)	124 (40.13)	105 (45.85)	159 (62.60)	
University	17 (5.96)	28 (9.33)	0 (0)	28 (12.23)	0 (0)	
Unknown	33 (11.58)	1 (0.33)	89 (28.80)	1 (0.44)	22 (8.66)	
Bed size, no. (%)						
<200	149 (52.28)	183 (61)	138 (44.66)	49 (21.40)	16 (6.30)	<0.001
200–400	109 (38.25)	69 (23)	112 (36.25)	180 (78.60)	194 (76.38)	
400–600	21 (7.37)	48 (16)	59 (19.09)	0 (0)	30 (11.81)	
>600	6 (2.11)	0 (0)	0 (0)	0 (0)	14 (5.51)	
No. of neurosurgeons	0	0	0	1	2	
No. of trauma surgeons	4	4	4	5	9	
Interhospital transfer, no. (%)						<0.001
No	273 (95.79)	287 (95.67)	291 (94.17)	208 (90.83)	211 (83.07)	
Yes	11 (3.86)	13 (4.33)	18 (5.83)	21 (9.17)	43 (16.93)	
Not known/not recorded	1 (0.35)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	

Boldface type indicates statistical significance.

centers (77%) than in low-volume centers (66%). In level III and level IV trauma centers, case volume quintiles were defined as ≤ 16, 17–21, 22–33, 34–56, and ≥ 57 cases/year, respectively. Table 3 outlines baseline patient- and hospital-level characteristics for level III and IV trauma centers by volume quintile.

Outcomes

Among level I trauma centers, adjusted mortality and complication rates, as well as total hospital and ICU stays, did not reveal significant differences with each stratum of increasing hospital volume (Table 4). Similarly, among level II trauma centers, a significant volume-outcome relationship was not observed for mortality, complications, or hospital discharge disposition (Table 5). However, unadjusted analysis showed total LOS was longer in higher-volume facilities compared to the lowest-volume facilities (unadjusted MD: Q2, 1.97 days, $p < 0.001$; Q3, 2.16 days, $p < 0.001$; Q4, 1.58 days, $p = 0.03$; Q5, 3.33 days, $p < 0.001$; reference = Q1). On adjusted analysis, LOS was significantly longer with the highest-volume stratum (Q5) compared to low-volume facilities (adjusted MD: Q5, 2.83 days, 95% CI 1.4–4.3 days, $p < 0.001$, reference = Q1). Similarly, unadjusted ICU stay was also longer in higher-volume facilities than in the lowest-volume facilities (unadjusted MD: Q2, 1.26 days, $p < 0.001$; Q3, 1.24 days, $p < 0.001$; Q4, 0.84 days, $p = 0.07$; Q5, 1.6 days, $p < 0.001$). However, adjusted analysis did not reveal a significant difference in ICU stay

with increasing volume quintile (adjusted MD: Q2, 1.13 days, 95% CI 0.41–1.85, $p = 0.002$; Q3, 1.12 days, 95% CI 0.42–2.00, $p = 0.003$; Q4, 0.64 days, 95% CI –0.25 to 1.54, $p = 0.16$; Q5, 1.32 days, 95% CI 0.38–2.26, $p = 0.006$).

For level III and level IV trauma centers (Table 6), the adjusted odds ratios suggested greater mortality with each quintile of severe TBI hospital volume but the relationships were statistically nonsignificant (low-medium volume: OR 1.71, 95% CI 0.66–4.38, $p = 0.27$; medium volume: OR 2.81, 95% CI 0.93–8.47, $p = 0.07$; medium-high volume: OR 1.18, 95% CI 0.30–4.57, $p = 0.81$; high volume: OR 2.48, 95% CI 0.68–9.08, $p = 0.17$; reference = low volume). Similarly, complication rates were also higher with increasing case volume but the relationships were statistically nonsignificant on adjusted analysis (low-medium volume: OR 2.39, 95% CI 0.73–7.87, $p = 0.15$; medium volume: OR 0.64, 95% CI 0.14–2.96, $p = 0.57$; medium-high volume: OR 2.87, 95% CI 0.54–15.20, $p = 0.21$; high volume: OR 3.92, 95% CI 0.70–21.85, $p = 0.12$; reference = low volume). Similarly, we found higher odds of nonhome discharge with higher-volume quintiles; however, these relationships were not statistically significant (low-medium volume: OR 1.63, 95% CI 0.50–5.35, $p = 0.42$; medium volume: OR 2.16, 95% CI 0.55–8.47, $p = 0.27$; medium-high volume: OR 3.34, 95% CI 0.89–12.43, $p = 0.07$; high volume: OR 1.16, 95% CI 0.19–7.21, $p = 0.87$; reference = low volume). Adjusted hospital LOS was approximately 5 days longer in the highest-volume stratum (≥ 57 cases/year,

TABLE 4. Level I trauma centers: odds ratios for mortality, complications, and nonhome discharge disposition and coefficients for hospital LOS and ICU stay, with hospital TBI volume as a predictor

Variable	Low Volume (≤357 cases/yr)	Low-Medium Volume (358–482 cases/yr)	Medium Volume (483–642 cases/yr)	Medium-High Volume (643–765 cases/yr)	High Volume (≥766 cases/yr)	p Value	p Value
No. of patients	10,503	10,538	10,588	10,685	9666		
Mortality, OR (95% CI)							
Unadjusted	Ref	0.96 (0.86, 1.07)	0.42	0.91 (0.81, 1.03)	0.13	0.93 (0.82, 1.05)	0.23
Adjusted	Ref	0.86 (0.75, 0.99)	0.04	0.99 (0.86, 1.15)	0.94	0.89 (0.76, 1.05)	0.18
Hospital LOS in days, MD (95% CI)							
Unadjusted	Ref	-0.53 (-1.75, 0.68)	0.39	1.09 (-0.21, 2.39)	0.10	0.4 (-1.03, 1.83)	0.59
Adjusted	Ref	0.15 (-0.95, 1.25)	0.79	1.23 (0.06, 2.41)	0.04	0.28 (-1.01, 1.58)	0.67
No. of ICU days, MD (95% CI)							
Unadjusted	Ref	-0.76 (-1.61, 0.1)	0.08	-0.24 (-1.16, 0.67)	0.61	-0.86 (-1.87, 0.15)	0.10
Adjusted	Ref	-0.65 (-1.42, 0.13)	0.10	-0.20 (-1.03, 0.64)	0.64	-0.83 (-1.75, 0.09)	0.08
Complications, OR (95% CI)							
Unadjusted	Ref	1.14 (0.80, 1.61)	0.47	1.26 (0.86, 1.83)	0.23	1.19 (0.78, 1.81)	0.41
Adjusted	Ref	1.30 (0.94, 1.79)	0.12	1.48 (1.05, 2.11)	0.03	1.13 (0.76, 1.66)	0.55
Nonhome discharge disposition, OR (95% CI)							
Unadjusted	Ref	1.19 (0.83, 1.72)	0.35	1.05 (0.71, 1.55)	0.80	1.26 (0.82, 1.93)	0.30
Adjusted	Ref	1.31 (0.91, 1.88)	0.14	1.13 (0.77, 1.67)	0.53	1.36 (0.89, 2.08)	0.15

Ref = reference.
Included covariates were age, sex, race, insurance status, comorbidities, hypotension, GCS score, ISS, type of surgical procedure, type of intracranial lesion, teaching status, bed size, and interhospital transfer in level I trauma centers.

TABLE 5. Level II trauma centers: odds ratios for mortality, complications, and nonhome discharge disposition and coefficients for hospital LOS and ICU stay, with hospital TBI volume as a predictor

Variable	Low Volume (≤121 cases/yr)	Low-Medium Volume (122–189 cases/yr)	Medium Volume (190–240 cases/yr)	Medium-High Volume (241–322 cases/yr)	High Volume (≥323 cases/yr)	p Value	p Value
No. of patients	4904	4795	5149	4701	4686		
Mortality, OR (95% CI)							
Unadjusted	Ref	0.93 (0.82, 1.06)	0.94 (0.82, 1.08)	1.03 (0.88, 1.2)	0.98 (0.83, 1.14)	0.73	0.76
Adjusted	Ref	0.88 (0.76, 1.02)	0.92 (0.79, 1.08)	0.99 (0.83, 1.17)	0.95 (0.79, 1.13)	0.89	0.55
Hospital LOS in days, MD (95% CI)							
Unadjusted	Ref	1.97 (0.82, 3.11)	2.16 (0.93, 3.38)	1.58 (0.18, 2.98)	3.33 (1.86, 4.8)	0.03	<0.001
Adjusted	Ref	1.54 (0.43, 2.64)	1.75 (0.54, 2.95)	1.09 (−0.27, 2.45)	2.83 (1.40, 4.26)	0.12	<0.001
No. of ICU days, MD (95% CI)							
Unadjusted	Ref	1.26 (0.52, 2)	1.24 (0.45, 2.04)	0.84 (−0.07, 1.75)	1.6 (0.64, 2.56)	0.07	<0.001
Adjusted	Ref	1.13 (0.41, 1.85)	1.12 (0.42, 2.00)	0.64 (−0.25, 1.54)	1.32 (0.38, 2.26)	0.16	0.006
Complications, OR (95% CI)							
Unadjusted	Ref	1.11 (0.80, 1.55)	0.84 (0.58, 1.21)	1.22 (0.80, 1.88)	1.41 (0.90, 2.22)	0.36	0.14
Adjusted	Ref	1.14 (0.80, 1.62)	0.94 (0.63, 1.40)	1.24 (0.78, 1.98)	1.50 (0.92, 2.44)	0.36	0.10
Nonhome discharge disposition, OR (95% CI)							
Unadjusted	Ref	1.51 (1.08, 2.12)	1.67 (1.14, 2.44)	1.48 (0.97, 2.26)	1.57 (1.00, 2.45)	0.066	0.047
Adjusted	Ref	1.70 (1.16, 2.48)	1.60 (1.05, 2.43)	1.57 (0.98, 2.49)	2.21 (1.35, 3.62)	0.060	0.002

Included covariates were age, sex, race, insurance status, comorbidities, hypotension, GCS score, ISS, type of surgical procedure, type of intracranial lesion, teaching status, bed size, and interhospital transfer in level II trauma centers. Boldface type indicates statistical significance.

TABLE 6. Level III and level IV trauma centers: odds ratios for mortality, complications, and nonhome discharge disposition and coefficients for hospital LOS and ICU stay, with hospital TBI volume as a predictor

Variable	Low Volume (≤16 cases/yr)	Low-Medium Volume (17–21 cases/yr)	Medium Volume (22–33 cases/yr)	Medium-High Volume (34–56 cases/yr)	High Volume (≥57 cases/yr)	p Value	p Value
No. of patients	285	300	309	229	254		
Mortality, OR (95% CI)							
Unadjusted	Ref	1.49 (0.72, 3.09)	1.94 (0.87, 4.32)	1.14 (0.41, 3.14)	2.62 (0.99, 6.91)	0.8	0.05
Adjusted	Ref	1.71 (0.66, 4.38)	2.81 (0.93, 8.47)	1.18 (0.30, 4.57)	2.48 (0.68, 9.08)	0.81	0.17
Hospital LOS in days, MD (95% CI)							
Unadjusted	Ref	1.77 (−0.16, 3.69)	2.05 (−0.07, 4.17)	2.66 (0.04, 5.28)	6.58 (3.99, 9.18)	0.05	<0.001
Adjusted	Ref	0.52 (−1.15, 2.18)	0.53 (−1.41, 2.47)	2.12 (−0.14, 4.38)	4.62 (2.29, 6.95)	0.07	<0.001
No. of ICU days, MD (95% CI)							
Unadjusted	Ref	1.11 (−0.31, 2.53)	1.36 (−0.2, 2.92)	1.74 (−0.17, 3.66)	4.91 (2.98, 6.84)	0.07	<0.001
Adjusted	Ref	0.20 (−0.97, 1.37)	0.11 (−1.25, 1.46)	1.27 (−0.28, 2.82)	3.19 (1.55, 4.84)	0.11	<0.001
Complications, OR (95% CI)							
Unadjusted	Ref	2.83 (0.92, 8.71)	0.94 (0.25, 3.58)	3.00 (0.63, 14.35)	6.52 (1.35, 31.39)	0.17	0.02
Adjusted	Ref	2.39 (0.73, 7.87)	0.64 (0.14, 2.96)	2.87 (0.54, 15.20)	3.92 (0.70, 21.85)	0.21	0.12
Nonhome discharge disposition, OR (95% CI)							
Unadjusted	Ref	2.13 (0.75, 6.08)	2.31 (0.72, 7.48)	2.98 (0.88, 10.09)	1.39 (0.30, 6.43)	0.08	0.67
Adjusted	Ref	1.63 (0.50, 5.35)	2.16 (0.55, 8.47)	3.34 (0.89, 12.43)	1.16 (0.19, 7.21)	0.07	0.87

Included covariates were age, sex, race, insurance status, comorbidities, hypotension, GCS score, ISS, type of surgical procedure, type of intracranial lesion, teaching status, bed size, and interhospital transfer in level III and level IV trauma centers. Boldface type indicates statistical significance.

$p < 0.001$). Adjusted ICU stay was approximately 3 days longer in the highest-volume stratum ($p < 0.001$).

Discussion

The aim of this study was to determine the relationship between case volume and in-hospital mortality, in-hospital complications, hospital LOS, and ICU stay in patients with severe TBI. Most other studies focusing on the hospital volume-outcome relationship have not studied the effect of the level designation of trauma centers and instead have pooled various levels of trauma centers in their analyses.^{1,20,21} In our investigation, however, we distinguished the effect of the level designation to see whether the volume stratum at a particular designation had an effect on patient outcome. Our study did not reveal a significant volume-outcome relationship for in-hospital mortality, complications, total hospital stay, and ICU stay among level I trauma centers. These results corroborate findings in an observational study by Wada et al., who did not find hospital TBI volume to be significantly associated with mortality in an analysis of a trauma database in Japan.²¹ However, we did observe an increase in adverse outcomes with increasing volume among level II, level III, and level IV trauma centers. Patients treated at level II, III, and IV trauma centers tended to stay longer in higher-volume facilities compared to patients in lower-volume centers, which is contradictory to findings in the literature.¹⁹ The effect size (odds ratios and confidence intervals) for higher mortality and complications with increasing volume at these centers was inconclusive, suggesting more studies are needed to investigate this relationship for level III and IV centers.

These results probably indicate that a higher annual severe TBI volume at a lower level of trauma center may be associated with adverse outcomes. Our study design was similar to a study conducted by Alali et al., which used data from the ACS Trauma Quality Improvement Program.¹ Their study included 111 level I and level II trauma centers that participated in the program during 2009–2011.¹ We included subjects enrolled over a longer period (2007–2014) in the NTDB, with a larger sample size. In addition, we performed a stratified analysis by level of trauma center since our hypothesis was that the effect of severe TBI hospital volume on outcomes would be different according to the type of hospital given the differences in resources available for trauma care. Since there are other criteria that determine the level of trauma center and associated outcomes, such as educational programs, resource allocation, and injury prevention, there may be other factors associated with outcomes in various levels of trauma centers rather than volume alone.² Therefore, our results demonstrate the complexity in improving the outcomes at trauma centers, which are probably influenced by factors other than volume itself. Glance et al. performed an NTDB study of 7371 patients with ISS ≥ 15 and also failed to demonstrate any association between trauma volume and in-hospital outcomes for both blunt and penetrating trauma.⁶

In our study, we only included subjects with an age ≥ 18 years, GCS score ≤ 8 , and AIS head score ≥ 3 . We excluded cases with penetrating trauma because most of these cases would be transferred to a level I or level II trauma center

and because these cases usually have worse outcomes than those in blunt trauma. Unlike previous studies, which have relied on ICD-9 and ICD-10 diagnosis codes, our inclusion definition of severe TBI used the GCS and ISS, thereby increasing the strength of our findings. We restricted our investigation to severe TBI cases defined as a GCS score ≤ 8 and AIS head score > 2 . We also performed adjustment for the type of intracranial pathology (subdural hematoma, epidural hematoma, traumatic subarachnoid hemorrhage, and cerebellar/brainstem lesions) and the surgical intervention performed.

Study Strengths and Limitations

The strengths of our study include a large sample size and adjustment for several patient-level factors such as insurance status, surgical procedure, case severity, type of intracranial pathology, and hospital-level characteristics. Using a clinical definition in place of administrative ICD-9 codes to identify severe TBI reduced the risk of selection bias due to inaccurate diagnosis. We used a stringent definition for statistical significance to avoid spurious associations.

However, there are limitations to this study. Despite adjustment for various confounders, there is a possibility of additional residual confounding, which could have affected our results. National databases allow pooling of a large number of cases, but there is limited granularity in the amount of clinically relevant variables available for adjustment. For instance, withdrawal-of-care decisions are not explicitly captured in the database. However, the number of cases from level III and level IV trauma centers was significantly smaller than those of level I and level II trauma centers, which could limit our ability to draw conclusions about in-hospital mortality at these centers. Second, inferences can only be made about associations, and there is limited evidence to support causality given the observational nature of our study. Third, residual unmeasured confounding that was not adjusted for in the current analysis may have influenced the results. For instance, information about rural versus urban hospital location could not be gathered, which could have an impact on transport to level I trauma centers from level III or level IV centers. Future investigations should also consider examining whether a change in volume with time at a given trauma center would impact outcomes.

Conclusions

Analysis based on the ACS NTDB did not reveal a significant volume-outcome relationship for severe TBI in level I trauma centers. However, we found that a higher volume of severe TBI in lower levels of trauma centers may be associated with longer LOSs. This finding may suggest a need for improved resource allocation for comparatively ill-equipped trauma centers, careful prehospital decision-making, and timely referral of patients with severe injury to a higher level of care, to improve outcomes in patients with TBI.

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Disclosures

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Author Contributions

Conception and design: Tsai, Goyal. Acquisition of data: Tsai, Goyal. Analysis and interpretation of data: Tsai, Goyal. Drafting the article: Tsai, Goyal. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Bydon. Statistical analysis: Tsai, Goyal, Wahood. Administrative/technical/material support: Bydon, Habermann. Study supervision: Bydon.

Supplemental Information

Online-Only Content

Supplemental material is available with the online version of the article.

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