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OBJECTIVE Treatment of cerebrovascular malformations has grown in complexity with the development of multimodal approaches, including microsurgery, endovascular treatments, and radiosurgery. In spite of this changing standard of care, the provision of care continues across a variety of settings. The authors sought to determine the risk of adverse outcome after treatment of patients with vascular malformations in the US. Patient, surgeon, and hospital characteristics, including volume, were tested as potential outcome predictors.

METHODS The authors examined data collected between 2000 and 2009 in the Nationwide Inpatient Sample (NIS) database, assessing safety, quality, and cost-effectiveness. They performed multivariate analyses of trends in microsurgical, radiosurgical, and endovascular treatment by hospital and surgeon volume, using death, routine discharge percentage, length of stay (LOS), complications, and hospital charges as end points. They further computed the value of care, which was defined as the ratio of the functional outcome (routine discharge percentage) to cost of care to the payer (hospital charges).

RESULTS The authors identified 8227 patients with vascular malformations who were treated at US hospitals. Hospitals and surgeons were classified by yearly case volume. Compared with low-volume hospitals (2 or fewer cases/year), high-volume hospitals (16 or more cases/year) had shorter LOS (3 vs 2 days, p = 0.005), higher total charges ($37,374 vs $19,986, p = 0.003), more frequent discharge to home (p < 0.001), and lower mortality rates (0.7% vs 1.16%, p = 0.010). High-volume surgeons (7 or more cases/year) likewise had superior outcomes compared with low-volume surgeons (1 or fewer cases/year), with shorter LOS (2 vs 3 days, p = 0.03), more frequent discharge to home (p < 0.001), and lower mortality rates (0.7% vs 1.10%, p = 0.005). Underlying these outcomes, the rates of intervention for surgery, angiography, embolization, and radiosurgery were likewise significantly different in high- versus low-volume practices.

Based on these results the authors modeled how outcomes might change if care were consolidated at designated centers of excellence (COEs), and found that on an annual basis, care at high-volume hospital COEs would result in 18.5 fewer deaths, 1252.1 fewer hospital days, 182.7 more discharges home without additional services, 48.5 fewer medical complications, and 117.4 fewer perioperative complications. Surgeon-level rates for high-volume COEs demonstrated an even larger benefit over current standards, with 27.4 fewer deaths, 10,713.7 fewer hospital days, a $51.6-million reduction in charges, 370.9 additional routine discharges, and reduced complications in all categories (27.8 fewer surgical, 198.0 fewer medical, and 32.1 fewer perioperative) compared with care at non-COEs.

CONCLUSIONS For patients with vascular malformations who were treated in the US between 2000 and 2009, treatment performed at high-volume centers was associated with significantly lower morbidity and, for high-volume surgeons, with lower mortality rates. These data suggest that treatment by high-volume institutions and surgeons will yield superior outcomes and superior value. The authors therefore advocate the creation of care paradigms that triage patients to high-volume institutions and surgeons, which can serve as cerebrovascular COEs.

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KEYWORDS arteriovenous malformation; cavernous malformation; Nationwide Inpatient Sample; epidemiology; outcomes; hospital bed size; teaching hospitals; volume-outcome analysis; vascular disorders

ABBREVIATIONS AHRQ = Agency for Healthcare Research and Quality; COE = center of excellence; CSC = Comprehensive Stroke Center; ED = emergency department; ICD-9-CM = International Classification of Diseases, Ninth Revision, Clinical Modification; LOS = length of stay; NIS = Nationwide Inpatient Sample.


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Health care in the US is performed across a wide spectrum of institutions varying in capacity and specialization. Treatment of cerebrovascular malformations has grown dramatically in complexity with the development of multimodal approaches, including microsurgery, endovascular therapies, and radiosurgery. Nonetheless, care for patients with these complex conditions continues across the spectrum of hospital types.

Examining the quality of care delivered across institution types allows for an objective assessment of the value of care delivered in different settings. Hospital and surgeon case volume have been shown to impact outcomes across a variety of subspecialties, including neurosurgery,1,2,4,5,13 cardiothoracic surgery,9,11 gastrointestinal surgery,3,7,12 and breast surgery.8 At present, there are no published reports of volume-outcome relationships for cerebrovascular malformations. Demonstration of these relationships is important in the current sociopolitical landscape, wherein legislation seeks to optimize cost and quality. Determining and examining the factors that contribute to differences in health outcomes6,9 is important for advancing the discussion in ways that benefit society as well as individual patients.

Herein, we used the Nationwide Inpatient Sample (NIS) database to assess the management of cerebrovascular malformations between 2000 and 2009, examining outcomes and charges over this period. The aims of this study were 2-fold: 1) to examine the relationship of volume to in-hospital mortality rate, routine discharge, length of stay (LOS), and complications; and 2) to compare the value of care across institutions.

Methods

Database

We obtained data from the NIS, a database sponsored by the Agency for Healthcare Research and Quality (AHRQ) of the US Department of Health and Human Services under the Healthcare Cost and Utilization Project. The NIS is the largest inpatient care database, representing approximately 20% of inpatient admissions to non-federal hospitals in the US, with approximately 8 million annual discharges from 1004 hospitals in 37 states. We specifically analyzed data collected within this database between 2000 and 2009 to determine trends in admissions and treatments for cerebrovascular malformations. The NIS is a de-identified data set that does not permit tracking of patients across multiple hospitalizations. For this reason, all outcome variables were assessed over the course of the index admission.

Inclusion and Exclusion Criteria

The NIS was queried for all hospital admissions with a primary diagnosis of “anomalies of the cerebrovascular system” by using the International Classification of Diseases, Ninth Revision, Clinical Modification (ICD-9-CM) diagnosis code 747.81, which consists primarily of arteriovenous and cavernous malformations. We also examined procedure trends by using appropriate codes for endovascular (ICD-9-CM principal procedure code 39.72) and open surgical (ICD-9-CM principal procedure code 01.59) interventions.

We identified potential postoperative complications following brain tumor surgery, which were coded according to the ICD-9-CM system as follows: neurological complications including those from infarction or hemorrhage (997.00–997.09); hematoma complicating a procedure (998.1–998.13); hydrocephalus (331–331.4); performance of ventriculostomy (02.2); mechanical ventilation (96.70, 96.72); pulmonary complications (518.5, 518.81, 518.84, 997.3); pneumonia (48.1, 48.2, 48.6); deep venous thrombosis complications (415.11, 453.40, 453.8, 453.9); cardiac complications (997.1, 41.0); wound infection complications (998.32, 998.51, 998.6, 998.81, 998.83); infectious complications (595.0, 595.9, 599.0); implant complications (996.2, 996.63, 996.75, 996.79); laceration (998.2); and decubitus ulcer (707.01–09).

Study End Points

Primary outcome measures within the database included total discharges, LOS, hospital charges, routine discharge percentage, and complications. The NIS delineates discharge as either death or discharge to one of a number of types of facilities classified by acuity of care. We used “routine discharge,” meaning discharge to home without services, as a surrogate for functional status.

Patient and Hospital Demographic Data

Patient age, sex, race, primary payer for the hospital stay, weekend admission, reason for admission, and admission type were extracted from the NIS. To evaluate for the effect of general medical comorbidity, a set of medical comorbidity markers described by Elixhauser et al. were used, with software provided by the AHRQ.6 A comorbidities index was created by summing each of the categories to calculate a composite comorbidity score.

We examined hospital size and teaching status, assessing correlations between these variables and the primary outcome measures. Hospital and surgeon volume were determined on a yearly basis. This was necessary given that the sampling method of the NIS means that a given surgeon or hospital will probably not be included in all years. Based on yearly volume rank, providers were stratified into volume quartiles as well as a highest-volume decile.

Volume Modeling

To estimate the impact of centralization of care, we developed models for outcomes that might plausibly be achieved at dedicated centers of excellence (COEs) and compared them to those for lower-volume providers. We determined the average number of annual admissions that would be eligible for treatment at COEs by discounting the mean admission rate to account for the sickest patients who died within 48 hours of admission. We computed the rates of mortality, LOS, routine discharge percentage, and medical, surgical, and perioperative complications for the COEs (taken as the mean rates for the top decile) as well as the non-COEs (taken as the mean rates for the bottom 90%).

Statistical Analysis

Correlations between demographic variables and the primary outcome measures were assessed using SPSS
(version 20; IBM Corp.), and JMP (version 10; SAS Institute) software. Statistical significance was calculated using the chi-square or Fisher exact test, Wilcoxon rank-sum test, nonparametric tests including Mann-Whitney and median tests, and binary and ordinal logistic regression analysis as appropriate. Normality between demographic variables and the hospital and surgeon quartile were assessed graphically and with JMP software, using Normal Q-Q Plot and absolute skewness statistic of ($k \leq 1$).

Hospital charges and value of care data were analyzed as logarithmic transformations to correct for positive skew. The independent samples Kruskal-Wallis test was used as a nonparametric alternative to the 1-way ANOVA for LOS. Stepwise forward logistic regression was used. We included all the patient demographic factors available in the NIS dataset, as shown in our tables. In our analysis, the final regression models include all statistically significant variables in the univariate analysis and variables that improved the model fit (increased the pseudo $R^2$ statistic). A $p$ value < 0.05 was considered significant.

We also computed a value parameter, defined as $(\text{outcome}/\text{cost})$. In this computation, routine discharge percentage was used as a surrogate for outcome, and mean hospital charges (in $100,000$) as a surrogate for cost. We additionally adjusted this parameter for risk, correcting for differences in emergency department (ED) admission rates among the different hospital sizes. Assuming an average routine discharge rate for ED admissions extrapolated from the available data, we computed a putative discharge rate for non-ED admissions for each hospital size, using this to compute a risk-adjusted parameter, defined as $(\text{risk-adjusted outcome}/\text{cost})$. We used the extrapolated non-ED routine discharge percentage for the risk-adjusted outcome, and again used mean hospital charges (in $100,000$) as a surrogate for cost to the payer.

**Results**

**Hospital Demographic Data**

We analyzed data from 8227 admissions, representing a 20% sample of the estimated 40,436 inpatient admissions for patients with a primary diagnosis of intracranial vascular malformation between 2000 and 2009. We analyzed the total number of discharges, mean LOS, mean charges, mean charges per day, and routine discharge percentage broken down by hospital size, teaching status, and diagnosis-specific hospital and surgeon volume. Overall, we found that the mean hospital volume decreased over the decade analyzed (Fig. 1).

**Overall Trends for Hospital Size**

The NIS categorizes hospital size into 3 region-adjusted tiers: small, medium, and large. Over the course of our study period, 80% of admissions occurred at large hospitals, 13% at medium hospitals, and 7% at small hospitals (Fig. 2A). The average LOS was significantly different among tiers, with stay for large hospitals averaging 4.3 days, 4.9 days for medium hospitals, and 6.7 days for small hospitals (Fig. 2B). Figure 2C demonstrates mean hospital charges. Large hospitals had mean charges of $46,000, medium hospitals had a mean charge of $54,000, and small hospitals had a mean charge of $57,000. There was a statistically significant difference when comparing large hospitals to either medium or small hospitals, although there was no significant difference between medium and small hospitals. The analysis also revealed a comparable routine discharge percentage at large and medium hospitals (88% and 87%, respectively), with small hospitals having a significantly smaller routine discharge percentage (71%) compared with large and medium hospitals (Fig. 2D).

We computed a value parameter, the ratio of simple routine discharge percentage (a surrogate for functional outcome) to hospital charges. This analysis reveals that medium and large hospitals provide a significantly higher value compared with small hospitals (Fig. 2E).

**Microsurgical Management Stratified by Hospital Size**

Twenty-one percent of all vascular malformation admissions were treated with microsurgical excision; 78% of these were at large hospitals, and 22% were at medium hospitals. There were no resections performed at small hospitals during this period. A similar proportion of vascular malformations (21%) was treated microsurgically at medium and large hospitals. However, patients undergoing surgery had a significantly shorter LOS at large hospitals (6.1 days for large hospitals and 7.3 days for medium hospitals). Large hospitals also had significantly lower charges for surgical patients ($63,000 for large hospitals and $68,000 for medium hospitals). Medium and large hospitals had comparable routine discharge percentages (84% at medium hospitals and 81% at large hospitals; $p = 0.09$). The computed value parameters for each are similar for medium (1.30) and large (1.28) hospitals ($p = 0.38$).

**Endovascular Management Stratified by Hospital Size**

Thirty-five percent of patients with vascular malformation underwent endovascular procedures, 87% of which were performed at large centers, compared with 13% at small and medium hospitals. Patients were significantly more likely to undergo therapeutic endovascular intervention at large hospitals than at medium and small hospitals.
Patients treated endovascularly at large hospitals had a significantly shorter LOS compared with those treated endovascularly at medium hospitals (3.1 vs 4.1 days). There were no significant differences in mean hospital charges ($53,000 for large hospitals and $52,000 for medium hospitals; p = 0.24) or routine discharge percentage (90% for large hospitals and 89% for medium hospitals; p = 0.32). The overall routine discharge percentage for patients who received endovascular treatment was significantly greater than for those who underwent surgical excision (91% vs 81%). Analysis of our computed value parameter revealed no significant differences between medium and large hospitals.

Overall Trends for Hospital Teaching Status

We next examined hospital teaching status. Eighty-six percent of admissions for vascular malformation occurred at teaching hospitals (Fig. 3A). Teaching hospitals had a similar LOS compared with nonteaching hospitals (5.0 days for teaching vs 4.3 days for nonteaching hospitals; p = 0.23) (Fig. 3B). Teaching hospitals had significantly higher mean charges of $49,000 compared with $34,000 for nonteaching hospitals (Fig. 3C). However, teaching hospitals also had a significantly higher routine discharge percentage (88%) compared with nonteaching hospitals (77%) (Fig. 3D). Analysis of our computed value parameter revealed no significant differences between teaching hospitals and nonteaching hospitals (Fig. 3E).

Microsurgical Management Stratified by Hospital Teaching Status

A significantly higher proportion of admissions for vascular malformation resulted in microsurgery at teaching hospitals (21.6%) compared with nonteaching hospitals (17.5%). Teaching hospitals have a significantly shorter LOS (6.5 days at teaching hospitals and 7.9 at nonteaching hospitals) and have similar mean hospital charges ($68,000 at teaching hospitals and $72,000 at nonteaching hospitals; p = 0.17). Additionally, teaching hospitals have a superior routine discharge percentage (82% at teaching hospitals and 71% at nonteaching hospitals). There is a significantly higher value quotient associated with care at teaching hospitals (1.22) compared with nonteaching hospitals (1.10), as shown in Fig. 3F.
Endovascular Management Stratified by Hospital Teaching Status

Overall, endovascular procedures were performed for 35% of admissions, with teaching hospitals performing 97% of these procedures. At teaching hospitals, 41% of patients underwent endovascular procedures, compared with 12% who were treated endovascularly at nonteaching hospitals; this difference was statistically significant. There was no significant difference in LOS between teaching hospitals (3.2 days) and nonteaching hospitals (2.1 days; \( p = 0.11 \)). The mean hospital charges were significantly less at teaching hospitals ($53,000) compared with nonteaching hospitals ($73,000). There was no significant difference in the routine discharge percentage between teaching hospitals (91%) and nonteaching hospitals (94%; \( p = 0.41 \)). A significantly higher value quotient was associated with care at teaching hospitals (1.71) compared with nonteaching hospitals (1.29), Fig. 3G.
We determined diagnosis-related volume at the hospital and surgeon level and assessed for associations between volume and outcome with both univariate and multivariate methods. Univariate analyses performed using basic demographic parameters found that age, sex, hemorrhage status on presentation, mortality rate, LOS, routine discharge percentage, charges, insurance, admission type, admission source, procedures performed, and comorbidity index all were significantly associated with hospital volume (Table 1). Surgeon volume was also significantly associated with almost all of these factors, except for age and total charges. Table 1 highlights some of the differences in rates between the lowest- and highest-volume quartiles for both hospital and surgeon volume.

Table 1. Univariate associations between demographic parameters and volume

<table>
<thead>
<tr>
<th>Demographic Parameter</th>
<th>Hospital Vol</th>
<th>p Value</th>
<th>Surgeon Vol</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Age (IQR) in yrs</td>
<td>44 (32–59)</td>
<td>39 (27–51)</td>
<td>&lt;0.001</td>
<td>40 (25–54)</td>
</tr>
<tr>
<td>Female (%)</td>
<td>49.6</td>
<td>52.8</td>
<td>&lt;0.001</td>
<td>48.5</td>
</tr>
<tr>
<td>Presenting hem (%)</td>
<td>34.3</td>
<td>11.3</td>
<td>&lt;0.001</td>
<td>37.7</td>
</tr>
<tr>
<td>Mortality (%)</td>
<td>1.16</td>
<td>0.7</td>
<td>0.010</td>
<td>1.1</td>
</tr>
<tr>
<td>LOS (IQR) in days</td>
<td>3 (2–5)</td>
<td>2 (1–5)</td>
<td>0.005</td>
<td>3 (1–5)</td>
</tr>
<tr>
<td>Routine discharge (%)</td>
<td>72.1</td>
<td>87.4</td>
<td>&lt;0.001</td>
<td>73.4</td>
</tr>
<tr>
<td>Total charges (IQR) in $</td>
<td>19,986 (10,627–37,321)</td>
<td>37,374 (23,150–62,948)</td>
<td>0.003</td>
<td>28,365 (14,489–51,802)</td>
</tr>
<tr>
<td>Insurance (%)</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td></td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Medicare</td>
<td>21.7</td>
<td>12.1</td>
<td>14.7</td>
<td>12.9</td>
</tr>
<tr>
<td>Medicaid</td>
<td>15.8</td>
<td>12.6</td>
<td>18.1</td>
<td>14.3</td>
</tr>
<tr>
<td>Private</td>
<td>49.1</td>
<td>67.3</td>
<td>54.7</td>
<td>61.4</td>
</tr>
<tr>
<td>Self-pay</td>
<td>8.8</td>
<td>3.6</td>
<td>6.6</td>
<td>5.2</td>
</tr>
<tr>
<td>Adm type (%)</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td></td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Emergency</td>
<td>54</td>
<td>10</td>
<td>38</td>
<td>17</td>
</tr>
<tr>
<td>Urgent</td>
<td>13</td>
<td>16</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Routine</td>
<td>32</td>
<td>74</td>
<td>49</td>
<td>69</td>
</tr>
<tr>
<td>Adm source (%)</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>ED</td>
<td>51</td>
<td>6</td>
<td>30</td>
<td>11</td>
</tr>
<tr>
<td>Acute care</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Long-term</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Routine</td>
<td>42</td>
<td>88</td>
<td>62</td>
<td>81</td>
</tr>
<tr>
<td>Procedure (%)</td>
<td>0.023</td>
<td></td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>Surgery</td>
<td>50.8</td>
<td>75.0</td>
<td>60.8</td>
<td>68.6</td>
</tr>
<tr>
<td>Angiography</td>
<td>60.3</td>
<td>87.3</td>
<td>75.5</td>
<td>84.5</td>
</tr>
<tr>
<td>Embolization</td>
<td>25.9</td>
<td>78.4</td>
<td>52.5</td>
<td>71.5</td>
</tr>
<tr>
<td>Radiosurgery</td>
<td>2.1</td>
<td>6.3</td>
<td>14.2</td>
<td>13.9</td>
</tr>
<tr>
<td>Comorb ind (%)</td>
<td>&lt;0.001</td>
<td></td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>&gt;2</td>
<td>13.42</td>
<td>10.28</td>
<td>12.82</td>
<td>3.57</td>
</tr>
</tbody>
</table>

Adm = admission; comorb ind = comorbidities index; hem = hemorrhage; IQR = interquartile range.
The mean values for parameters are compared between the lowest- and highest-volume quartiles for both hospital and surgeon volume.

Hospital and Surgeon Volume

We determined diagnosis-related volume at the hospital and surgeon level and assessed for associations between volume and outcome with both univariate and multivariate methods. Univariate analyses performed using basic demographic parameters found that age, sex, hemorrhage status on presentation, mortality rate, LOS, routine discharge percentage, charges, insurance, admission type, admission source, procedures performed, and comorbidity index all were significantly associated with hospital volume (Table 1). Surgeon volume was also significantly associated with almost all of these factors, except for age and total charges. Table 1 highlights some of the differences in rates between the highest- and lowest-volume providers. High-volume hospitals and surgeons treated a significantly higher proportion of privately insured patients than their low-volume counterparts, who saw more patients with public insurance (i.e., Medicare and Medicaid). High-volume providers also had higher rates of routine admissions, with low-volume providers seeing a larger proportion of patients through EDs. High-volume providers also tended to see patients with fewer comorbidities. Low-volume surgeons and hospitals provided fewer of all procedure types, except for radiosurgery: surgery, angiography, and embolization.

Multivariate analyses were performed to assess for associations between volume and the primary outcomes of LOS, total charges, routine discharge percentage, complications, and mortality rates. Table 2 shows how age, sex, comorbidity index, hospital volume, and surgeon volume were associated with outcomes. Of all of the variables, the comorbidity index had the most sizeable impact on outcome for LOS, total charges, and routine discharge percentage; however, although the comorbidity index was still significantly associated with mortality rates, the largest-magnitude impact was for hospital volume. Hospital volume was significantly associated with the primary outcomes shown in Table 2, except in the case of total charges. Surgeon volume was significantly associated only with LOS. Hospital volume consistently demonstrated a more profound impact than did surgeon volume. Of the outcomes analyzed, hospital and surgeon volume had the largest impact on routine discharge percentage.
Mortality rates for all cases trended similarly for both surgeon and hospital volume, with rates increasing with volume through the third quartile, but in both instances the highest-volume decile demonstrated dramatically lower inpatient mortality rates (Figs. 4A and B, and 5A and B). Outcomes were further broken out into surgical versus nonsurgical cases. High-volume surgeons and hospitals both experience a dramatic reduction in the mortality rate among nonsurgical patients (Figs. 4B and 5B). Surgical patients at low-volume hospitals have the highest mortality rates, with higher-volume hospitals showing an initial drop in rates, with a subsequent steady rise in mortality (Fig. 4B).

For all quartiles, the LOS was shorter for nonsurgical patients. Nonsurgical patients showed a steady but significant diminution in LOS as volume increased. Surgical patients showed a similar trend, with diminished LOS in the highest 2 quartiles by hospital volume (Fig. 4C and D).

Surgical patients consistently incurred higher charges than nonsurgical patients, regardless of volume quartile (Figs. 4F and 5F). Hospital volume correlated positively with charges for both surgical and nonsurgical patients, peaking in the third quartile but dropping among the highest-volume-quartile hospitals (Fig. 4E and F). In contrast, surgeon volume for surgical patients demonstrated an inverse relationship; there were declining charges with increasing volume, except in the highest quartile (Fig. 5E and F).

Surgeon volume did not significantly impact the routine discharge percentage among surgical patients; however, hospital volume showed a positive correlation with improved routine discharge percentage. Nonsurgical patients showed a similar positive correlation between routine discharge percentage and both hospital and surgeon volume (Figs. 4G and H, and 5G and H).

Table 3 demonstrates associations between hospital and surgeon volume and complications. Grouping complications by type (i.e., surgical, perioperative, or medical), both hospital and surgeon volume were positively correlated with reduced incidence of complications in multivariate analyses. High-volume hospitals had fewer perioperative (OR 0.41, 95% CI 0.23–0.62) and medical (OR 0.81, 95% CI 0.72–0.90) complications. High-volume surgeons likewise experienced fewer medical complications (OR 0.69, 95% CI 0.60–0.78) and also had fewer surgical complications (OR 0.54, 95% CI 0.36–0.81). Among other factors strongly correlated with increased complications were hemorrhage and teaching status. Hemorrhage on presentation correlates with all types of complications to a high degree (surgical: OR 4.81, 95% CI 3.40–6.70; perioperative: OR 5.42, 95% CI 2.78–10.00; medical: OR 6.07, 95% CI 4.79–7.67). Teaching hospital status likewise was strongly correlated with poor surgical complication rates (OR 6.88, 95% CI 2.70–24.48).

**Volume Modeling for COEs**

To estimate the impact of centralization of care, we developed models for outcomes that might plausibly be achieved at dedicated COEs and compared them with those for lower-volume providers. We made assumptions that all but the most critically ill patients would be preferentially transferred to designated COEs after initial medical stabilization. Table 4 relates expected outcomes differences that might be expected under this COE arrangement compared with the outcomes achieved at present. Given that the magnitude of volume-outcomes relationships differs at the hospital and surgeon level, we computed differences in outcomes using both rates. We found that on an annual basis, high-volume hospital COEs would result in 18.5 fewer deaths, 1252.1 fewer hospital days, 182.7 more medical complications, and 117.4 fewer perioperative complications. These COEs would result in approximately $71.7 million in additional charges and 7.8 more surgical complications. Surgeon-level rates for high-volume COEs demonstrated an even larger benefit over current standards, with 27.4 fewer deaths, 10,713.7 fewer hospital days, a $51.6-million reduction in charges, 370.9 additional routine discharges, and reduced complications in all categories (27.8 surgical, 198.0 medical, and 32.1 perioperative).

**Discussion**

We show that volume for both surgeons and hospitals significantly impacts patient outcomes both in terms of value of care and functional outcomes. Compared with low-volume hospitals, high-volume hospitals had shorter LOS, lower complication rates, more frequent routine discharge to home, and lower mortality rates. High-volume surgeons likewise had significantly better outcomes than low-volume surgeons, demonstrating shorter LOS, more frequent routine discharge, lower complication rates, and lower mortality rates.

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TABLE 2. Effect of patient and hospital factors on outcomes, including LOS, total charges, routine discharge proportion, and mortality

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Age (invert)†</th>
<th>Female</th>
<th>Comorb Ind</th>
<th>Hemi‡</th>
<th>Nonroutine Adm</th>
<th>Bed Size</th>
<th>Teaching</th>
<th>Hospital Vol</th>
<th>Surgeon Vol</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS</td>
<td>0.02</td>
<td>NS</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.05</td>
<td>NS</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>Total charges</td>
<td>NS</td>
<td>NS</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.003</td>
<td>NS</td>
<td>0.003</td>
<td>&lt;0.001</td>
<td>NS</td>
</tr>
<tr>
<td>Routine discharge</td>
<td>&lt;0.0001; 0.61</td>
<td>0.040; 0.90</td>
<td>&lt;0.0001; 0.33</td>
<td>&lt;0.0001; 0.20</td>
<td>&lt;0.0001; 0.54</td>
<td>0.0001; 1.26</td>
<td>NS</td>
<td>&lt;0.0001; 1.59</td>
<td>NS</td>
</tr>
<tr>
<td>Mortality</td>
<td>&lt;0.0001; 0.65</td>
<td>0.55–0.77</td>
<td>&lt;0.0001; 13.46</td>
<td>&lt;0.0001; 3.36</td>
<td>&lt;0.0001; 13.46</td>
<td>&lt;0.0001; 13.46</td>
<td>&lt;0.0001; 13.46</td>
<td>NS</td>
<td>&lt;0.0001; 1.51</td>
</tr>
</tbody>
</table>

NS = not significant.
* Data expressed as p value alone or as p value; OR (95% CI).
† Age represents age strata, and comparisons are to highest ages strata.
‡ Status at presentation.
Our multivariate models show that for many outcomes of interest, hospital volume correlates more strongly with outcome than does surgeon volume. Although it is not numerically possible for a high-volume surgeon to practice in a low-volume hospital, it is possible for multiple lower-volume surgeons to practice in a high-volume hospital. Put in different terms, the surgeon effect is a subset of the hospital effect. These data suggest that pre- and postoperative care provided by high-volume hospitals is an essential component and that the systems in place in such institu-

FIG. 4. Bar graphs showing outcomes computed based on hospital case volume for each volume quartile, as well as for the highest-volume decile. Mortality rate (A and B), LOS (C and D), hospital charges (E and F), and routine discharge proportion (G and H) were computed for all admissions (A, C, E, and G) and were subsequently stratified by treatment status (B, D, F, and H) based on whether patients received surgery during their index admission. The error bars represent the SEM.
tions provide value beyond what the surgeon alone can provide. Even though these hospitals tend to have higher charges than some of the lower-volume hospitals, this is probably because of their increased procedure rates. Regardless, the value provided is superior given the better outcomes that they yield. Interestingly, even in nonsurgical cases the correlations between provider volume and outcome hold as well. This further supports the assertion that systems in place with high-volume providers yield benefit beyond what the surgeon’s technical skills could provide.
Because patients who have a hemorrhagic presentation can be more medically ill, have worse outcomes, and be more prone to suffer complications, we included hemorrhage status on presentation in our analyses. High-volume hospitals and surgeons were found to treat a lower proportion of patients who had hemorrhage present on admission, and had a higher proportion of routine elective admissions. Although high-volume hospitals and providers may have a more favorable patient mix from the standpoint of having fewer medically ill patients with ruptured malformations, multivariate analyses taking into account hemorrhage status, hospital admission status, and admission source, all of which can serve as surrogates for severity of illness, show that the volume-outcome relationship is robust.

The volume-outcome effects demonstrated by these data strongly support assertions that the public good would be served by consolidating care for such complex neurovascular conditions into designated COEs. Although these data are correlative and do not prove causation, the effects are robust and reproducible across a number of complex procedure types, both within and outside of neurosurgery. Consolidating treatment of certain conditions, of course, has serious implications that challenge the current US medical system in ways that some find difficult. There are questions about the freedom of practitioners to operate, impacts on patients and families implicit in transfer to nonlocal treatment centers, and implications for exposure to trainees. Several other nations have adopted centralization as the modus operandi for medical care, to the extent that nearly all aneurysms, arteriovenous malformations, cavernous malformations, and so on are treated exclusively at a single center or at a limited number of centers nationwide. As a result, practitioners at these centers accrue a wealth of experience related to these conditions and truly become experts in their care. This stands in contrast to the current US system, in which a large proportion of complex vascular lesions are treated in hospitals that see fewer than 5 such lesions yearly. Although individual practitioners might enjoy the variety these cases add to their practice and truly believe that they are doing the best that they can for their patients, statistically speaking such low-volume centers perform much more poorly. From a population perspective, patients would therefore be better served at higher-volume centers.

Transfer from low- to high-volume centers has been questioned out of concern for medical stability and inconvenience for family members. In the case of cavernous and arteriovenous malformations, once a patient is initially medically stabilized, transfer is considered relatively safe. The risk of rehemorrhage is lower than for aneurysms, and the time sensitivity of treatment is not as acute as is the case for ischemic stroke. Based on volume modeling from these data, to achieve results comparable to the decile volume providers, the US would need to designate approximately 46 hospitals and 150 surgeons to take care of these patients. Although the distribution of such centers would probably need to be a compromise between geographical and population considerations, this is approximately one per state, an arrangement that would be roughly comparable in terms of distance to systems successfully implemented in Europe. Whereas this might be somewhat inconvenient for family members wishing to have treatment closer to home, the higher likelihood of good patient outcomes should help to assuage concerns.

Finally, neurosurgical trainees would be impacted by efforts to consolidate into COEs. Although not all neurosurgery training programs would be designated as COEs, it is possible to arrange for affiliations between training programs and their “locally” designated COE such that trainees could rotate through the centers and receive a focused exposure to high-quality care paradigms. This would similarly facilitate high-quality collaborative research in this area of neurosurgery that has heretofore suffered from relatively sparse institutional data.

Some have suggested that the existing Comprehensive Stroke Center (CSC) designation by the Joint Commission would be an appropriate means of establishing high-volume centers. However, as the program currently exists, the volume thresholds for CSC designation are too low (15 aneurysms treated annually) and are not specifically targeted to vascular malformations. The result of the low volume threshold is that there are too many CSCs, and thus the potentially positive impacts that could be realized by substantially boosting volume at designated centers would be diluted. We therefore propose that a different designation is required, whether it be administered through organized neurosurgery itself or as an additional designation from the Joint Commission.

### TABLE 3. Effect of patient and hospital factors, hospital volume, and surgeon volume on complications

<table>
<thead>
<tr>
<th>Complication</th>
<th>Patient or Hospital Factor*</th>
<th>Age (invert)</th>
<th>Female</th>
<th>Comorb Ind</th>
<th>Hem</th>
<th>Nonroutine Adm</th>
<th>Bed Size</th>
<th>Teaching</th>
<th>Hospital Vol</th>
<th>Surgeon Vol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surgical</td>
<td>&lt;0.0001; 0.38 (0.28–0.52)</td>
<td>NS</td>
<td>NS</td>
<td>&lt;0.0001; 4.81 (3.40–6.70)</td>
<td>NS</td>
<td>NS</td>
<td>0.0004; 6.88 (2.70–24.48)</td>
<td>NS</td>
<td>0.002; 0.54 (0.36–0.81)</td>
<td></td>
</tr>
<tr>
<td>Periop</td>
<td>NS</td>
<td>0.012; 0.49 (0.28–0.86)</td>
<td>0.010; 2.78 (1.30–5.46)</td>
<td>&lt;0.0001; 5.42 (2.78–10.00)</td>
<td>0.043; 0.54 (0.28–0.98)</td>
<td>0.007; NA</td>
<td>&lt;0.0001; NA</td>
<td>&lt;0.0001; 0.41 (0.23–0.62)</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Medical</td>
<td>&lt;0.0001 (3.88 (1.30–4.80))</td>
<td>&lt;0.0001; 6.07 (4.79–7.67)</td>
<td>NS</td>
<td>NS</td>
<td>0.0002; 1.64 (1.25–2.16)</td>
<td>0.0001; 0.81 (0.72–0.90)</td>
<td>&lt;0.0001; 0.69 (0.60–0.78)</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NA = not available.

Variables are grouped by complication type and adjusted for hospital bed size, hospital teaching status, patient age, patient sex, hemorrhage status on presentation, patient presenting comorbidities, admission status, surgeon volume (for hospital-level calculations), and hospital volume (for surgeon-level calculations).

* Data expressed as p value; OR (95% CI).
Beyond the direct effect of volume, hospital characteristics such as bed size and teaching status are also associated with improved outcome in most cases. Large hospitals have a shorter LOS and lower charges to the payer for similar outcomes for all microsurgical and endovascular cases when compared with smaller hospitals. Large hospitals therefore provide the greatest value of care for management of vascular malformations, which can be interpreted to mean that large hospitals provide the most cost-effective care from the payer’s standpoint. It remains uncertain how actual costs vary by hospital size. Cost-to-charge ratios are not available in the NIS for the entirety of our study period, but as these data become available, future analyses may be able to examine this further. Nonetheless, it is clear that the value to the payer is highest at large hospitals.

Teaching hospitals consistently achieve a superior outcome with a similar LOS for all patients in spite of increased medical and surgical complication rates. When looking at all cases, regardless of treatment, teaching hospitals have a higher cost of care. However, this changes dramatically for operative intervention, for which teaching hospitals not only have superior outcomes but shorter LOS and comparable overall cost of care. Teaching hospitals therefore appear to provide superior care at a higher cost for management of vascular malformations overall, and superior care at a comparable cost for operative intervention.

Value is a difficult entity to calculate definitively. The value quotient is defined as the ratio of outcomes to costs, but depending on the particular measures we use to represent outcomes and costs, there is a large variability in the result. Nonetheless, value is a vital parameter for examining the cost-effectiveness of health care, with increasing import as health care costs continue to rise. National databases such as the NIS offer a limited set of parameters by which researchers can define outcomes. These parameters are typically generic characteristics related to the hospital stay, and it is impossible to know neurological outcome or true functional status. In the present study, we chose routine discharge percentage as a proxy for functional outcome. Furthermore, cost differs based on the perspective from which we examine it. The hospital charges that are available in the NIS database are the charges made to the payer, and in turn society, but they do not necessarily represent costs incurred in the process of providing care, nor do they represent money received from the payer for that care. Given available data, we are limited to calculating a value of the service provided to the payer, but we cannot determine the cost-effectiveness of the care provided from the hospital’s perspective. Looking forward, such analyses will become important to ensuring that care is provided in a way that truly maximizes available resources.

Risk adjustment is another difficulty inherent to value comparisons. Patient populations can differ dramatically between institutions on the basis of coexisting comorbidities and underlying health as well as severity of the primary disease process. Several authors, such as Elixhauser, have developed systems using data from the NIS to account for major medical comorbidities. Risk adjustment must be made to truly attribute differences in value to the care system itself; otherwise such differences may be confounded by demographic differences. Unfortunately, a parameter we cannot directly measure in these data is the severity of the primary disease process, such as with the Spetzler-Martin grading system in the case of arteriovenous malformations. Future analyses would benefit from inclusion of such data in risk adjustment to ascertain differences in patient populations more accurately and to improve estimates of the outcomes and value of care delivered.

In spite of limitations inherent to such analyses, the strong correlation between outcomes and the factors analyzed, hospital volume, teaching volume, hospital size, and teaching status, argue that we should seek to institute systems that preferentially direct patients with vascular malformations to large, high-volume centers. Regionalization of care for vascular malformations would be likely to provide superior outcomes to patients and better value to payers and society.

**Conclusions**

For patients with vascular malformations who were treated in the US between 2000 and 2009, treatment performed at high-volume centers was associated with significantly lower morbidity and lower complication rates, and,
for high-volume surgeons, lower mortality rates. These data suggest that the treatment of vascular malformations by high-volume institutions and surgeons will provide overall superior outcomes and superior value. We therefore advocate the creation of care paradigms that triage patients to high-volume institutions and surgeons, which can serve as COEs for cerebrovascular management.

References


Disclosures
The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions
Conception and design: both authors. Acquisition of data: Davies. Analysis and interpretation of data: Davies. Drafting the article: Davies. Critically revising the article: Davies. Reviewed submitted version of manuscript: both authors. Statistical analysis: Davies. Study supervision: Lawton.

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