Impact of neurosurgeon specialization on patient outcomes for intracranial and spinal surgery: a retrospective analysis of the Nationwide Inpatient Sample 1998–2009

*Brandon A. McCutcheon, MD, MPP,^{1,2} Brian R. Hirshman, MD, MS,¹ Brandon C. Gabel, MD,¹ Michael W. Heffner, BA,¹ Logan P. Marcus, MD, MS,¹ Tyler S. Cole, MD,³ Clark C. Chen, MD, PhD,¹ David C. Chang, PhD, MBA, MPH,^{1,4} and Bob S. Carter, MD, PhD¹

¹Department of Neurosurgery, University of California, San Diego, La Jolla, California; ²Department of Neurologic Surgery, Mayo Clinic and Mayo Clinic Foundation, Rochester, Minnesota; ³Barrow Neurological Institute, Phoenix, Arizona; and ⁴Department of Surgery, Massachusetts General Hospital, Boston, Massachusetts

OBJECTIVE The subspecialization of neurosurgical practice is an ongoing trend in modern neurosurgery. However, it remains unclear whether the degree of surgeon specialization is associated with improved patient outcomes. The authors hypothesized that a trend toward increased neurosurgeon specialization was associated with improved patient morbidity and mortality rates.

METHODS The Nationwide Inpatient Sample (NIS) was used (1998–2009). Patients were included in a spinal analysis cohort for instrumented spine surgery involving the cervical spine (*International Classification of Diseases, Ninth Revision, Clinical Modification* [ICD-9-CM] codes 81.31–81.33, 81.01–81.03, 84.61–84.62, and 84.66) or lumbar spine (codes 81.04–81.08, 81.34–81.38, 84.64–84.65, and 84.68). A cranial analysis cohort consisted of patients receiving a parenchymal excision or lobectomy operation (codes 01.53 and 01.59). Surgeon specialization was measured using unique surgeon identifiers in the NIS and defined as the proportion of a surgeon's total practice dedicated to cranial or spinal cases.

RESULTS A total of 46,029 and 231,875 patients were identified in the cranial and spinal analysis cohorts, respectively. On multivariate analysis in the cranial analysis cohort (after controlling for overall surgeon volume, patient demographic data/comorbidities, hospital characteristics, and admitting source), each percentage-point increase in a surgeon's cranial specialization (that is, the proportion of cranial cases) was associated with a 0.0060 reduction in the log odds of patient mortality (95% CI 0.0034–0.0086) and a 0.0042 reduction in the log odds of morbidity (95% CI 0.0032–0.0052). This resulted in a 15% difference in the predicted probability of mortality for neurosurgeons at the 75th versus the 25th percentile of cranial specialization. In the spinal analysis cohort, each percentage-point increase in a surgeon's spinal specialization was associated with a 0.0122 reduction in the log odds of mortality (95% CI 0.0074–0.0170) and a 0.0058 reduction in the log odds of morbidity (95% CI 0.0049–0.0067). This resulted in a 26.8% difference in the predicted probability of mortality for neurosurgeons at the 75th versus the 25th percentile of spinal specialization.

CONCLUSIONS For both spinal and cranial surgery patient cohorts derived from the NIS database, increased surgeon specialization was significantly and independently associated with improved mortality and morbidity rates, even after controlling for overall case volume.

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KEY WORDS specialization; NIS; multivariate analysis; surgical outcomes research; spinal fusion; lobectomy; parenchymal excision; Nationwide Inpatient Sample

ABBREVIATIONS ICD-9-CM = *International Classification of Diseases, Ninth Revision, Clinical Modification*; IQR = interquartile range; NIS = Nationwide Inpatient Sample.

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* Drs. McCutcheon and Hirshman contributed equally to this work.

OVER the past half century, there has been a tendency toward subspecialization. By the 1970s, there were more than 20 recognized medical and surgical subspecialties with their own board-certification processes.⁴ As a result, surgical subspecialization is becoming the norm throughout the health care community.^{6,15}

Similar trends have been observed within neurosurgery. Although graduates of accredited neurosurgical programs are licensed to practice the gamut of neurosurgery, few exercise this prerogative. For example, hospitals routinely require fellowship training to perform pediatric operations.^{11,18} Many neurosurgeons, moreover, gravitate toward a particular subspecialty out of choice. The reasons behind this are myriad but include the operating surgeon's natural inclinations, fellowship training, technical abilities, and/or research interests. Academic departments may also encourage faculty members to subspecialize.

Data from multiple surgical specialties seem to support surgeon specialization. For example, Golledge et al. found that surgical subspecialization was associated with improved outcomes in patients with breast cancer.¹³ Compared with general surgeons, vascular surgeons have lower mortality rates among patients when operating on abdominal aortic aneurysms.¹⁰ Other work has demonstrated that patients of cardiothoracic surgeons have better outcomes after undergoing lung resection compared with those of general surgeons.¹⁴ Data on neurosurgical subspecialization are less robust, but some authors have shown that gross-total resection of intracranial neoplasms is higher in pediatric patients if the surgeon is subspecialized in pediatrics.^{2,19}

This study uses a national data set to investigate the impact of neurosurgical subspecialization on patient outcomes for both cranial and spinal surgery. We hypothesized that a trend toward increased neurosurgeon specialization was associated with improved patient outcomes.

Methods

Data Source

The Nationwide Inpatient Sample (NIS) from 1998 to 2009 was used as the data source for this study. These data are maintained by the Healthcare Cost and Utilization Project of the Agency for Healthcare Research and Quality. The NIS is the largest national administrative database for all payer categories and captures 100% of discharges from a 20% stratified sample of US hospitals. Because the NIS uses a stratified randomized sampling technique, the data contained in the NIS are representative of and generalizable to US hospitals. Within the NIS, the unit of analysis is a patient admission. Each admission record includes *International Classification of Diseases, Ninth Revision, Clinical Modification* (ICD-9-CM) codes for the 15 most important procedures performed during that admission, as well as a unique identifier enabling identification of the primary provider.

Identification of Neurosurgeons and Surgeon Operative Volume

A provider was considered for inclusion in the study if he or she performed any of the cranial or spinal operations

listed in Table 1. Providers were linked across multiple patient admissions using a unique identifier as done in similar studies using the NIS.^{3,7,12,16} Total operative volume for a provider-year was equal to the total number of cranial and spinal operations performed in a calendar year. Because the provider identifiers do not correlate across calendar years,¹² our unit of analysis for this work was the neurosurgeon-year, defined as the set of all patients who underwent operations by a neurosurgeon during a calendar year.

To ensure that our data set contained only neurosurgeons, 2 exclusion criteria were applied. First, because spine operations were also performed by orthopedic surgeons, surgeons were excluded from analysis if they did not perform at least 1 cranial operation as defined in Table 1. Second, to ensure that providers were actually active staff at their hospitals, neurosurgeons were excluded if they were not associated with a total volume of at least 50 cases in a given year.

Neurosurgeon Specialization

Neurosurgeon spinal specialization was computed for each neurosurgeon-year by determining the percentage of spinal operations (Table 1) of the total cranial and spinal operations performed by each provider in a given year. Cranial specialization was computed for each neurosurgeon-year by determining the percentage of cranial operations of the total cranial and spinal volume in a given year. For discussion in the present study, when a surgeon devoted more than 75% of their practice to either cranial or spinal surgery, they are described as highly specialized in either cranial or spinal surgery.

Analysis Cohorts

To ensure a viable comparison between the types of procedures done by surgeons of varying degrees of specialization, we chose a set of cranial and spinal codes that 1) had a degree of technical difficulty such that mortality differences might be apparent, and 2) were highly represented across the range of specialization. First, a cranial analysis cohort included all patients who underwent a cranial operation involving parenchymal excision or lobectomy (ICD-9-CM codes 01.53 and 01.59); these are codes that are typically used for mass lesion excision in the brain. A second spinal analysis cohort included all patients who underwent any of the following instrumented spinal operations: primary fusion of the cervical (codes 81.01–81.03) or lumbar (codes 81.04–81.08) spine, refusion of the cervical (codes 81.31–81.33) or lumbar (codes 81.34–81.38) spine, primary insertion of disc prosthesis of the cervical (codes 84.61–84.62) or lumbar (codes 84.64–84.65) spine, or revision of a disc prosthesis in the cervical (code 84.66) or lumbar (code 84.68) spine.

Patient Outcomes

Two primary end points were assessed during this study. The first end point was inpatient mortality, as recorded in the NIS. The second end point, adverse discharge disposition, has been used in previous neurosurgical studies within the NIS⁸ and was defined as discharge

TABLE 1. Cranial and spine operation codes

Code	Description
Cranial	
01.01	Cisternal puncture
01.02	Ventriculopuncture through previously implanted catheter
01.09	Other cranial puncture
01.10	Intracranial pressure monitoring
01.11	Closed percutaneous needle biopsy of cerebral meninges
01.12	Open biopsy of cerebral meninges
01.13	Closed percutaneous needle biopsy of brain
01.14	Open biopsy of brain
01.15	Biopsy of skull
01.16	Intracranial oxygen monitoring
01.21	Incision & drainage of cranial sinus
01.22	Removal of intracranial neurostimulator lead(s)
01.24	Other craniotomy
01.25	Other craniectomy
01.26	Insertion of catheter(s) into cranial cavity or tissue
01.28	Placement of intracerebral catheter(s) via bur hole(s)
01.31	Incision of cerebral meninges
01.32	Lobotomy & tractotomy
01.39	Other incision of brain
01.41	Ops on thalamus
01.42	Ops on globus pallidus
01.51	Excision of lesion or tissue of cerebral meninges
01.52	Hemispherectomy
01.53	Lobectomy of brain
01.59	Other excision or destruction of lesion or tissue of brain
02.11	Simple suture of dura mater of brain
02.12	Other repair of cerebral meninges
02.13	Ligation of meningeal vessel
02.14	Choroid plexectomy
02.31	Ventricular shunt to structure in head & neck
02.32	Ventricular shunt to circulatory system
02.33	Ventricular shunt to thoracic cavity
02.34	Ventricular shunt to abdominal cavity & organs
02.39	Other ops to establish drainage of ventricle
02.41	Irrigation & exploration of ventricular shunt
02.42	Replacement of ventricular shunt
02.43	Removal of ventricular shunt
02.92	Repair of brain
02.93	Implantation or replacement of intracranial neurostimulator lead(s)
02.96	Insertion of sphenoidal electrodes
Spine	
03.01	Removal of foreign body from spinal canal
03.02	Reopening of laminectomy site
03.09	Other exploration & decompression of spinal canal
03.21	Percutaneous chordotomy
03.29	Other chordotomy
03.32	Biopsy of spinal cord or spinal meninges
03.51	Repair of spinal meningocele

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TABLE 1. Cranial and spine operation codes

Code	Description
Spine (continued)	
03.52	Repair of spinal myelomeningocele
03.53	Repair of vertebral fracture
03.59	Other repair & plastic operations on spinal cord structures
03.71	Spinal subarachnoid-peritoneal shunt
03.72	Spinal subarachnoid-ureteral shunt
03.79	Other shunt of spinal theca
03.93	Implantation or replacement of spinal neurostimulator lead(s)
03.94	Removal of spinal neurostimulator lead(s)
03.97	Revision of spinal thecal shunt
03.98	Removal of spinal thecal shunt
80.50	Excision or destruction of intervertebral disc, unspecified
80.51	Excision of intervertebral disc
80.52	Intervertebral chemonucleolysis
80.53	Repair of the annulus fibrosus w/ graft or prosthesis
80.54	Other & unspecified repair of the annulus fibrosus
80.59	Other destruction of intervertebral disc
81.00	Spinal fusion, not otherwise specified
81.01	Atlas-axis spinal fusion
81.02	Other cervical fusion, anterior technique
81.03	Other cervical fusion, posterior technique
81.04	Dorsal & dorsolumbar fusion, anterior technique
81.05	Dorsal & dorsolumbar fusion, posterior technique
81.06	Lumbar & lumbosacral fusion, anterior technique
81.07	Lumbar & lumbosacral fusion, lateral transverse process technique
81.08	Lumbar & lumbosacral fusion, posterior technique
81.30	Refusion of spine, not otherwise specified
81.31	Refusion of atlas-axis spine
81.32	Refusion of other cervical spine, anterior technique
81.33	Refusion of other cervical spine, posterior technique
81.34	Refusion of dorsal & dorsolumbar spine, anterior technique
81.35	Refusion of dorsal & dorsolumbar spine, posterior technique
81.36	Refusion of lumbar & lumbosacral spine, anterior technique
81.37	Refusion of lumbar & lumbosacral spine, lateral transverse process technique
81.38	Refusion of lumbar & lumbosacral spine, posterior technique
81.39	Refusion of spine, not elsewhere classified
81.62	Fusion or refusion of 2–3 vertebrae
81.63	Fusion or refusion of 4–8 vertebrae
81.64	Fusion or refusion of 9 or more vertebrae
84.51	Insertion of interbody spinal fusion device
84.59	Insertion of other spinal devices
84.60	Insertion of spinal disc prosthesis, not otherwise specified
84.65	Insertion of total spinal disc prosthesis, lumbosacral
84.66	Revision or replacement of artificial spinal disc prosthesis, cervical

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TABLE 1. Cranial and spine operation codes

Code	Description
Spine (<i>continued</i>)	
84.67	Revision or replacement of artificial spinal disc prosthesis, thoracic
84.68	Revision or replacement of artificial spinal disc prosthesis, lumbosacral
84.69	Revision or replacement of artificial spinal disc prosthesis, not otherwise specified
84.80	Insertion or replacement of interspinous process device(s)
84.81	Revision of interspinous process device(s)
84.82	Insertion or replacement of pedicle-based dynamic stabilization device(s)
84.83	Revision of pedicle-based dynamic stabilization device(s)
84.84	Insertion or replacement of facet replacement device(s)
84.85	Revision of facet replacement device(s)

to a short-term hospital, skilled nursing facility, intermediate care facility, home health care, another nursing or rehabilitation facility, or death.

Controlling for Covariates

Multiple factors are known to influence neurosurgical outcomes, many of which are coded in the NIS. All models controlled for the effects of insurance status, race, sex, age, hospital teaching status, urban versus rural hospital location, whether the operation was completed in an elective setting, and year in which the procedure was performed. Insurance status was separated into 3 groups: patients with private insurance or Medicare, patients with Medicaid, and uninsured patients. Patient comorbidities were assessed using a calculated Charlson Comorbidity Index as defined by Romano et al.¹⁷ A binary variable specifying whether patients were admitted from a long-term health care facility was also used.

Replications of Results

A replication of cranial specialization results was performed using a cohort of patients undergoing surgical clip occlusion of an intracranial aneurysm (ICD-9-CM code 39.51). An additional replication of spinal specialization results was performed using a cohort of patients undergoing spinal decompression surgery (code 03.09).

Statistical Analysis

Statistical analysis was performed using commercially available software (STATA/SE 11.2; StataCorp LLC). Multivariate analyses were performed using logistic regression models, adjusting for surgeon spinal or cranial volume, surgeon specialization (that is, percent of spinal or cranial volume relative to total volume), patient insurance status, race, Charlson Comorbidity Index, age, hospital teaching status, hospital urbanicity, year, and adverse admission status. All tests were 2-sided and statistical significance was established at $p < 0.05$.

Results

Data Set

A total of 231,875 patients were identified as having received an instrumented spine surgery of either the lumbar or cervical spine and were included in the spinal analysis cohort. A total of 46,029 patients were identified as having received an operation for parenchymal excision of a mass lesion or a lobectomy and were included in the cranial analysis cohort. Patient demographic data for both cohorts are provided in Table 2.

There were 4304 neurosurgeon-years with a total volume of ≥ 50 cases identified as having completed at least 1 operation in the cranial analysis cohort. Among these surgeons, the median total volume of cranial and spinal cases identified in the NIS in a given year was 114 cases (interquartile range [IQR] 80–161 cases) (Table 3). The median number of cranial cases performed by these surgeons in a given year was 29 (IQR 17–49 cases). The median degree of cranial specialization (that is, the percentage of total cases that were cranial in nature) was 25% (IQR 14%–43%) in a given year for neurosurgeons operating in the cranial analysis cohort.

There were 4656 neurosurgeon-years with a total volume of ≥ 50 cases identified as having completed at least 1 operation in the spinal analysis cohort. The median total volume of spinal and cranial cases performed by neurosurgeons in the spinal analysis cohort in a given year in the NIS was 114 cases (IQR 79–162 cases) (Table 3). Among neurosurgeons operating in the spinal analysis cohort, the median number of spinal cases performed in a given year was 81 (IQR 52–130 cases). The median degree of spinal specialization (that is, the percentage of total cases dedicated to operations of the spine) was 80% (IQR 63%–90%) for neurosurgeons operating in the spinal analysis cohort.

Specialization and Mortality Patterns Among Neurosurgeons Performing Cranial and Spinal Neurosurgery

A series of histograms display the distribution of neurosurgeon specialization, total cranial and spinal case volume, and total cranial and spinal patient mortality rates by surgeon specialization. Figure 1A reveals that most neurosurgeons concentrate their practice in spinal neurosurgery. Approximately one-half (49.9%) of all neurosurgeons devoted $> 75\%$ of their practice to spine surgery, and 79.8% of all neurosurgeons devoted $> 50\%$ of their practice to spinal neurosurgery. In contrast, only 10.2% of all neurosurgeons devoted $> 75\%$ of their practice to cranial surgery, and 20.2% of neurosurgeons devoted $> 50\%$ of their practice to cranial surgery.

Results When Operating Within Specialty

When operating in their majority specialized domain, highly specialized surgeons had a lower than expected rate of mortality. Highly specialized cranial surgeons operated on 24.5% of all cranial surgery patients (Fig. 1B), accounting for 15.4% of all cranial surgery deaths (Fig. 1C), and had lower patient mortality rates per surgeon on cranial operations than less specialized surgeons (Fig. 1D). Simi-

TABLE 2. Characteristics from the NIS of patients undergoing cranial and spine procedures (1998–2009)

Variable	Available Cranial Data	Cranial	Available Spine Data	Spine
Age in yrs	46,029 (100.0)	48.5 (52.0)*	231,875 (100.0)	52.6 (52.0)*
Race/ethnicity	38,443 (84.0)		192,937 (83.0)	
White		29,960 (77.9)		163,185 (84.6)
Black		3520 (9.2)		16,082 (8.3)
Hispanic		3138 (8.2)		8464 (4.4)
Asian or Pacific Islander		481 (1.3)		1202 (0.6)
Native American		185 (0.5)		620 (0.3)
Other		1159 (3.0)		3384 (1.8)
Sex	46,024 (100.0)		231,850 (100.0)	
Male		24,173 (52.5)		111,304 (48.0)
Female		21,851 (47.5)		120,546 (52.0)
Calendar year	46,029 (100.0)		231,875 (100.0)	
1998		2969 (6.5)		10,889 (4.7)
1999		3482 (7.6)		14,563 (6.3)
2000		3663 (7.9)		16,327 (7.0)
2001		3676 (8.0)		15,358 (6.6)
2002		3800 (8.3)		17,367 (7.5)
2003		4641 (10.1)		23,709 (10.2)
2004		4178 (9.1)		21,088 (9.1)
2005		4003 (8.7)		20,665 (8.9)
2006		3370 (7.3)		21,711 (9.4)
2007		4022 (8.7)		20,953 (9.0)
2008		4461 (9.7)		26,635 (11.5)
2009		3764 (8.2)		22,610 (9.8)
Charlson Comorbidity Index	46,029 (100.0)	2.64 (2.0)*	231,875 (100.0)	0.41 (0.0)*
Expected primary payer	44,066 (96.0)		203,400 (88.0)	
Medicare or private insurance		36,684 (83.3)		186,135 (91.5)
Medicaid		5462 (12.4)		12,865 (6.3)
Uninsured		1920 (4.4)		4400 (2.2)
Hospital teaching status	45,882 (100.0)		230,522 (99.0)	
Teaching		36,335 (79.2)		133,821 (58.1)
Nonteaching		9547 (20.8)		96,701 (42.0)
Hospital location	46,029 (100.0)		231,875 (100.0)	
Urban		44,515 (96.7)		222,442 (95.9)
Rural		1514 (3.3)		9433 (4.1)
Admission type	32,167 (70.0)		174,429 (75.0)	
Elective		17,300 (53.8)		149,475 (85.7)
Nonelective		14,867 (46.2)		24,954 (14.3)
Admission source	46,029 (100.0)		231,875 (100.0)	
Routine		45,365 (98.6)		230,888 (99.6)
Transfer from another health facility		664 (1.4)		987 (0.4)

Data are the number of patients (%) unless otherwise specified.

* Data are the mean (median).

larly, specialized spinal surgeons performed 74.6% of all spinal surgeries (Fig. 1E) but accounted for only 57.0% of all spinal surgery deaths (Fig. 1F) and had lower patient mortality rates per surgeon on spine operations than less specialized neurosurgeons (Fig. 1G).

We noted that increases in surgeon cranial specialization are associated with lower rates of cranial mortality

across all levels of surgeon total volume in a stepwise fashion (Fig. 2A). We noted similar trends when investigating adverse discharge disposition in the cranial analysis cohort. Similar trends were observed when investigating mortality rates and adverse discharge disposition in the spinal analysis cohort. Figure 2B–D demonstrates a reverse J-shape curve, in which rates of mortality and adverse discharge

TABLE 3. Surgeon case mix characteristics among surgeons identified in the spinal and cranial cohorts

Cohort	Median (IQR)
Spine	
Surgeon vol of cases, no.	81 (52–130)
Surgeon % of total cases	80 (63–90)
Surgeon total vol of cases, no.	114 (79–162)
Cranial	
Surgeon vol of cases, no.	29 (17–49)
Surgeon % of total cases	25 (14–43)
Surgeon total vol of cases, no.	114 (80–161)

disposition seem to increase slightly for neurosurgeons with the very highest levels of specialization.

Specialization Demonstrates a Dose-Response Type of Relationship With Patient Mortality

Figure 3 displays mortality rates for each surgeon in a given year. Each neurosurgeon-year is displayed as a point

in a scatter plot of overall operative volume (cranial plus spinal cases) versus specialization in the cranial analysis cohort and spinal analysis cohort. Coloring indicates the quintile grouping of mortality for each neurosurgeon-year plotted.

As seen in Fig. 3 (left), neurosurgeons with the highest cranial mortality rates form a cluster in the lower left region of the scatter plot, which represents low volume and low cranial specialization. Higher degrees of cranial specialization, even among surgeons with relatively low volume, are still seen to be associated with significant improvements in mortality rate. Neurosurgeons in the quintile with the lowest patient mortality tended to demonstrate $\geq 50\%$ cranial specialization across a wide range of total yearly case volumes. The cranial surgery mortality rate and range in each quintile are provided in Table 4.

In Fig. 3 (right), we note similar trends in the spinal analysis cohort. Neurosurgeons with the highest spinal surgery mortality rates cluster in the lower left region of the scatter plot, which represents low volume and low specialization. Surgeons with the lowest spinal surgery mortality rates cluster in the upper right corner of the plot,

FIG. 1. Histograms showing the number of neurosurgeons (A) as a function of neurosurgeon specialization (x axis), indicating that most neurosurgeons are specialized in spinal surgery. B–D: Histograms showing the number of cranial surgery patients (B) and deaths (C), and the mortality rate per surgeon (D). E–G: Histograms showing the number of spine surgery patients (E) and deaths (F), and the mortality rate per surgeon (G), respectively. In panels D and G, colors represent mortality rate ranges from lower (green) to higher (red).

FIG. 2. A and B: Mortality rate and adverse discharge disposition for cranial surgeries (y axis) shown for 4 groups of surgeons categorized by total surgical volume (1st quartile < 92 cases per year, 2nd quartile 92–127 cases per year, 3rd quartile 128–176 cases per year, 4th quartile > 176 cases per year). The x axis shows neurosurgeon specialization subcategorized into quintiles according to the percentage of overall practice that is cranial surgery. **C and D:** Mortality rate and adverse discharge disposition for spinal surgeries (y axis) shown for 4 groups of surgeons categorized by total surgical volume (1st quartile < 110 cases per year, 2nd quartile 110–157 cases per year, 3rd quartile 158–225 cases per year, 4th quartile > 225 cases per year). The x axis shows neurosurgeon specialization subcategorized into quintiles according to the percentage of overall practice that is spinal surgery.

which represents greater volume and specialization. Overall operative volume seems to have a stronger association with improvements in mortality rate in the spinal analysis cohort relative to the cranial analysis cohort. In Table 4, the mortality rate and range in each quintile for spinal surgery are shown.

Magnitude of the Specialization Effect in Cranial Surgery

When patient mortality was investigated in a logistic regression model in the cranial analysis cohort (Table 5), surgeon specialization and surgeon total volume were significantly associated with patient mortality. Using surgeon total volume as a continuous variable, each additional sur-

FIG. 3. Scatter plots displaying mortality rates (*green* represents lower, *red* represents higher) as a function of case volume (x axis) and percent spinal or cranial surgery specialization (y axis) among surgeons with at least 1 patient fatality. The cranial data (*left*) illustrate a clear trend toward lower mortality rates with increasing specialization; however a weaker trend toward increased case volume is noted. In the spine data (*right*), a clear trend toward lower mortality rates can be seen with both increasing volume and increasing specialization. Histograms summarizing mortality rates as a function of case volume (above the scatter plots) and specialization (to the right of scatter plots) are provided as summary statistics.

gical case was associated with a 0.0010 (95% CI 0.0002–0.0019) reduction in the log odds of mortality. With each percentage-point increase in surgeon cranial specialization, there was an associated 0.0060 reduction in the log odds of patient mortality (95% CI 0.0034–0.0086). A marginal effects analysis demonstrated that the magnitude of this association was such that there was a 15% reduction in the predicted probability of mortality as neurosurgeon cranial specialization increased from 14% (25th percentile) to 43% (75th percentile).

When multivariate analysis was performed, both surgeon total volume and surgeon specialization were associated with significant reductions in the predicted probability of adverse discharge disposition for patients in the cranial analysis cohort. Each additional case in a surgeon's total volume was associated with a 0.0009 reduction in the log odds of adverse discharge (95% CI 0.0006–0.0013). Likewise, each percentage-point increase in surgeon cra-

nial specialization was associated with a 0.0042 reduction in the log odds of patient adverse discharge disposition (95% CI 0.0032–0.0052). When comparing surgeons operating at the 75th percentile of surgeon cranial specialization with those operating at the 25th percentile, we observed a 6.1% difference in the predicted probability of patient adverse discharge disposition.

Magnitude of the Specialization Effect in Spinal Surgery

In the spinal analysis cohort, multivariate analysis revealed that increases in surgeon total volume were associated with a downward trend in the predicted probability of patient mortality (Table 6). However, this trend was not statistically significant. The degree of spinal specialization was associated with a significant reduction in the predicted probability of patient mortality after risk adjustment for available patient and hospital information. Each percent-

TABLE 4. Characteristics of surgeon mortality quintiles for cranial and spinal analysis cohorts

Quintile	Patient Mortality Rate (%) by Surgeon, Range	No. of Surgeon-Yrs in Quintile	No. of Patients in Quintile	No. of Deaths in Quintile	Overall Patient Mortality Rate (%) in Quintile
Cranial					
1	0.69–5.58	253	9009	299	3.32
2	5.58–9.09	255	4157	312	7.51
3	9.09–14.3	270	2939	350	11.91
4	14.3–25.0	254	2041	398	19.50
5	25.0–100	179	700	276	39.43
Spinal					
1	0.26–1.03	126	19,224	133	0.69
2	1.03–1.72	128	10,475	140	1.34
3	1.72–2.60	122	6616	139	2.10
4	2.60–4.25	125	4932	162	3.28
5	4.25–100	126	2581	170	6.59

TABLE 5. Results of multivariate logistic regression analysis displaying log odds of death and adverse discharge for patients undergoing cranial surgery

Variable	Adjusted Mortality, n = 36,681		Adjusted Adverse Discharge, n = 36,640	
	Log Odds (95% CI)	p Value	Log Odds (95% CI)	p Value
Surgeon case mix				
Total vol	-0.0010 (-0.0019 to -0.0002)	0.015	-0.0009 (-0.0013 to -0.0006)	<0.001
% of total cases, cranial	-0.0060 (-0.0086 to -0.0034)	<0.001	-0.0042 (-0.0052 to -0.0032)	<0.001

age-point increase in the proportion of cases dedicated to spinal practice was significantly associated with a 0.0122 reduction in the log odds of mortality (95% CI 0.0074–0.0170). When marginal effects analysis was performed, a 26.8% reduction in the predicted probability of patient mortality was observed as neurosurgeon spinal specialization increased from 63% (25th percentile) to 90% (75th percentile).

Multivariate analysis of adverse discharge disposition in the spinal analysis cohort demonstrated a significant association with surgeon total volume and specialization. Each additional neurosurgical case was associated with a 0.0007 reduction in the log odds of adverse discharge disposition (95% CI 0.0006–0.0009). Each percentage-point increase in spinal specialization was associated with a 0.0058 reduction in the log odds of adverse discharge disposition (95% CI 0.0049–0.0067). This resulted in a 9.6% reduction in the predicted probability of adverse discharge disposition between surgeons operating at the 75th percentile and the 25th percentile for spinal specialization.

Sensitivity Analysis

A sensitivity analysis was performed to investigate whether the results described above were reproducible in the population of patients undergoing surgical clip occlusion of an intracranial aneurysm (ICD-9-CM code 39.51) in the NIS data set. On multivariate analysis, neurosurgeon cranial specialization was again associated with a significant and independent reduction in patient mortality (log odds -0.006, 95% CI -0.009 to -0.002), such that the predicted probability of mortality decreased by 14.4% as neurosurgeon specialization increased from 14% (25th percentile) to 43% (75th percentile) after controlling for other variables. On multivariable analysis fitted for adverse discharge disposition, increasing neurosurgeon cranial specialization was associated with a small but significant reduction in the log odds of adverse discharge disposition (log odds -0.005, 95% CI -0.007 to -0.003). This translated to a 5.8% reduction in the predicted probability

of adverse discharge between the 25th and 75th percentiles of neurosurgeon cranial specialization.

An additional sensitivity analysis was performed to investigate whether similar trends with regard to surgeon specialization could be observed in the population of patients undergoing spinal decompression surgery (ICD-9-CM code 03.09). On multivariate analysis, neurosurgeon specialization was associated with a reduction in both mortality (log odds -0.017, 95% CI -0.021 to -0.012) and adverse discharge disposition (log odds -0.006, 95% CI -0.007 to -0.005). There was a 5.2% associated reduction in the predicted probability of mortality as neurosurgeon spinal specialization increased from 63% (25th percentile) to 90% (75th percentile). Similarly, there was a 9.9% associated reduction in the predicted probability of adverse discharge disposition as neurosurgeon specialization increased from the 25th to the 75th percentile.

Discussion

This study investigated the association between spinal and cranial specialization and patient outcomes among neurological surgeons included in the NIS database. Our data suggest that both the volume of cases and the subspecialization of that volume are associated with improved patient outcomes. Because neurosurgeons are trained in both spinal and cranial neurosurgical procedures and they frequently develop a practice profile that involves performing both types of procedures, and because the degree of specialization can be modified for individual surgeons in a group, it is of interest to study the effect of practice specialization on patient outcomes to inform decision making by individual surgeons or groups of surgeons regarding the impact of their specialization choices.

When patient mortality was investigated using a logistic regression model, increased surgeon specialization was significantly associated with reductions in the predicted probability of death in both the cranial and spinal analysis cohorts. Total volume was also significantly associated

TABLE 6. Results of multivariate logistic regression analysis displaying log odds of death and adverse discharge for patients undergoing spine surgery

Variable	Adjusted Mortality, n = 168,856		Adjusted Adverse Discharge, n = 168,708	
	Log Odds (95% CI)	p Value	Log Odds (95% CI)	p Value
Surgeon case mix				
Total vol	-0.0010 (-0.0021 to 0.0001)	0.062	-0.0007 (-0.0009 to -0.0006)	<0.001
% of total cases, spine	-0.0122 (-0.0170 to -0.0074)	<0.001	-0.0058 (-0.0067 to -0.0049)	<0.001

with a reduction in patient mortality in the cranial analysis cohort. Similar trends were elucidated for patient adverse discharge disposition. In general, the trends of improved mortality and discharge outcomes with improved specialization increased monotonically, as shown in Fig. 2A–D. However, we did note a slight uptick in mortality rate and adverse morbidity among the most highly specialized spine surgeons. This finding may be explained if highly specialized spine surgeons take on significantly more complex or difficult operative cases.

The findings in this study suggest that both higher volume and subspecialization are associated with a beneficial impact on patient mortality and morbidity. The finding that surgeon case volume correlates with outcome is not unique and has been extensively documented as the volume-outcome relationship in the medical and surgical literature.^{5,20} This study adds an additional dimension to the traditional volume-outcome relationship: surgeon specialization. The distinction between higher volume and specialization is important because it provides neurosurgeons with 2 unique opportunities to improve their outcomes. It is a nontrivial challenge to simply increase the quantity of cases in one's practice. However, it may be more feasible to organize with partners and establish a division of labor such that each individual surgeon is maintaining a more specialized practice.

This analysis raises the question of whether tipping points of specialization exist such that above a given level of specialization, the outcomes in the area of major specialization are so good and outcomes in the area of minor specialization are so poor that there may be a significant benefit for the surgeon to become fully specialized in 1 clinical domain. This would probably occur near the extremes of either spinal or cranial specialization. Because of this phenomenon, in some situations, it may be prudent for a surgeon to organize their practice to be more fully specialized in 1 particular domain of neurosurgery if they are working in an environment that is permissive for such restructuring.

We envision that the data presented herein could serve as a basis for modeling how neurosurgical groups could achieve an optimal specialization within their groups to ensure the best overall outcomes for the population they serve. For example, a 3-surgeon group may require 3 surgeons with the typical practice mix of 80% spine and 20% cranial to meet the demands of call coverage, whereas an 8-surgeon group may be best served with 2 majority cranial practitioners and 6 majority spine practitioners to improve clinical outcomes. Carefully designed future studies may further illustrate the benefits of such changes.

These results may also impact the organization of practice in academic groups, where teaching and/or research may comprise a significant portion of a given faculty member's efforts. These data suggest that lower-volume, but highly specialized, cranial or spinal surgeons can achieve excellent outcomes. Thus, a faculty member who elects to devote significant professional effort to research or teaching may retain expert-level outcomes through specialization.

This study is strengthened by the fact that the NIS is a large, generalizable data set that is representative of the general US population. The NIS data set also allowed us

to test a hypothesis that would be difficult to explore using alternate methodologies. To date, the NIS has been used in numerous studies to investigate the association between provider volume and patient outcome.¹⁹ Because specialization was defined as the ratio of spinal or cranial volume relative to total volume, which is readily available for calculation in the NIS, the NIS is a valid data source for this study. This study also investigated the role of subspecialization in the 2 major clinical divisions within neurosurgery: spinal and cranial surgery. Therefore, the results are particularly germane to multiple stakeholders within the neurosurgical community.

This study is associated with all of the attendant weaknesses attributed to administrative data sets. Errors in administrative coding exist. However, it is unlikely that such errors are biased toward specialized versus unspecialized neurosurgeons in this study, and therefore these errors are unlikely to have an impact on our results. Highly specific clinical details and imaging are notably absent from the data used for this study. As a result, risk adjustment is imperfect, and it is difficult to fully assess other patient or operative characteristics that may be relevant. In addition, the ICD-9-CM codes used for patient selection are specific, and the results of this study may not be generalizable to other neurosurgical operations.

Moreover, for neurosurgeons who operate at > 1 facility, this study may not capture the entirety of their practice and the total volumes presented may underestimate true volumes. The NIS also does not provide information regarding whether a neurosurgeon has completed fellowship training. Others may prefer to define specialization according to whether fellowship training was completed, and this study cannot provide insight in this regard.

Given limitations in the granularity of data provided in the NIS, future studies will be needed to determine in more detail the impact of specific subspecialization (e.g., tumor, cerebrovascular, trauma) on patient outcomes. Further studies that use data sources with longer follow-up and functional outcome measures (e.g., long-term neurological sequelae or patient disability indices at 1 year) will also be needed.

There is a trend toward centralized medical and surgical care across the United States. Large, centralized practices may organize as a group of generalists or maintain a division of labor according to surgeon subspecialization. This study suggests that subspecialized neurosurgeons are associated with improvements in patient morbidity and mortality when operating in their realm of specialization. This study may, therefore, argue in favor of earlier subspecialty training.

Conclusions

Taken as a whole, our data suggest that the best outcomes are seen among surgeons who perform surgeries within their realm of subspecialization. Our data further suggest that even surgeons with an overall lower-volume practice may achieve excellent outcomes by specialization. These results also confirm those of prior studies, which have shown that high-volume surgeons have lower rates of inpatient mortality and adverse discharge disposition for both spinal and cranial surgery. These findings support the

current trend toward subspecialization seen in our contemporary health care system.

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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: Carter, McCutcheon, Hirshman, Chen, Chang. Acquisition of data: Carter, McCutcheon, Hirshman, Chen, Chang. Analysis and interpretation of data: McCutcheon, Hirshman, Heffner, Marcus, Cole. Drafting the article: McCutcheon, Hirshman, Gabel, Heffner. Critically revising the article: all authors. Reviewed submitted version of manuscript: Carter, Hirshman, Gabel, Heffner, Marcus, Cole, Chen, Chang. Approved the final version of the manuscript on behalf of all authors: Carter. Statistical analysis: McCutcheon, Hirshman. Administrative/technical/material support: Carter, McCutcheon, Heffner. Study supervision: Carter, McCutcheon.

Correspondence

Bob S. Carter, Massachusetts General Hospital, 55 Fruit St., Boston, MA 02114. email: bccarter@mgh.harvard.edu.