National trends in cerebral bypass surgery in the United States, 2002–2014

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OBJECTIVE Cerebral bypass procedures are microsurgical techniques to augment or restore cerebral blood flow when treating a number of brain vascular diseases including moyamoya disease, occlusive vascular disease, and cerebral aneurysms. With advances in endovascular therapy and evolving evidence-based guidelines, it has been suggested that cerebral bypass procedures are in a state of decline. Here, the authors characterize the national trends in cerebral bypass surgery in the United States from 2002 to 2014.

METHODS Using the National (Nationwide) Inpatient Sample, the authors extracted for analysis the data on all adult patients who had undergone cerebral bypass as indicated by ICD-9-CM procedure code 34.28. Indications for bypass procedures, patient demographics, healthcare costs, and regional variations are described. Results were stratified by indication for cerebral bypass including moyamoya disease, occlusive vascular disease, and cerebral aneurysms. Predictors of inpatient complications and death were evaluated using multivariable logistic regression analysis.

RESULTS From 2002 to 2014, there was an increase in the annual number of cerebral bypass surgeries performed in the United States. This increase reflected a growth in the number of cerebral bypass procedures performed for adult moyamoya disease, whereas cases performed for occlusive vascular disease or cerebral aneurysms declined. Inpatient complication rates for cerebral bypass performed for moyamoya disease, vascular occlusive disease, and cerebral aneurysm were 13.2%, 25.1%, and 56.3%, respectively. Rates of iatrogenic stroke ranged from 3.8% to 20.4%, and mortality rates were 0.3%, 1.4%, and 7.8% for moyamoya disease, occlusive vascular disease, and cerebral aneurysms, respectively. Multivariate logistic regression confirmed that cerebral bypass for vascular occlusive disease or cerebral aneurysm is a statistically significant predictor of inpatient complications and death. Mean healthcare costs of cerebral bypass remained unchanged from 2002 to 2014 and varied with treatment indication: moyamoya disease \$38,406 ± \$483, vascular occlusive disease \$46,618 ± \$774, and aneurysm \$111,753 ± \$2381.

CONCLUSIONS The number of cerebral bypass surgeries performed for adult revascularization has increased in the United States from 2002 to 2014. Rising rates of surgical bypass reflect a greater proportion of surgeries performed for moyamoya disease, whereas bypasses performed for vascular occlusive disease and aneurysms are decreasing. Despite evolving indications, cerebral bypass remains an important surgical tool in the modern endovascular era and may be increasing in use. Stagnant complication rates highlight the need for continued interest in advancing available bypass techniques or technologies to improve patient outcomes.

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KEYWORDS cerebral bypass; national trends; moyamoya disease; cerebral aneurysm; vascular occlusion

CEREBRAL bypass surgery has undergone near constant evolution since its introduction in 1969.^{34,35} A number of innovative microsurgical techniques have been described and tailored to treat a diverse array of disease entities, including moyamoya disease, athero-

sclerotic vascular occlusive disease, and complex cerebral aneurysms, or to facilitate vessel sacrifice with the resection of skull base tumors.¹⁸ However, evidence-based guidelines have been comparatively slower to evolve. The results of randomized controlled trials, such as the Carotid

ABBREVIATIONS AHRQ = Agency for Healthcare Research and Quality; COSS = Carotid Occlusion Surgery Study; ECIC = extracranial-intracranial; NIS = National (Nationwide) Inpatient Sample; PED = Pipeline embolization device; US = United States.

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Occlusion Surgery Study (COSS) or the Extracranial-Intracranial Bypass Trial, have been discouraging for select indications.^{3,25} The development of endovascular technology, such as the flow-diverting stent, and stereotactic radiosurgery has led to treatment alternatives for complex cerebral aneurysms and skull base neoplasia, respectively.^{16,22}

The convergence of these factors has led to a decline in cerebral bypasses over the past decade at one institution.³² Whether similar trends are present at the national level is currently unknown. Here, we utilize the largest all-payer hospital-based database, the National (Nationwide) Inpatient Sample (NIS), to characterize national trends in cerebral bypass surgery from 2002 to 2014 in the United States (US). Unlike prior reports, we show that there has been a modest increase in the number of cerebral bypasses performed nationally, a finding largely attributed to a rise in the surgical treatment of moyamoya disease. The changing indications for cerebral vascularization are characterized, and we explore whether these changes influence patient outcomes or the national healthcare costs attributed to cerebral bypass at a national level.

Methods

Study Population

Data were extracted from the Agency for Healthcare Research and Quality (AHRQ)-sponsored NIS for the period from 2002 to 2014. Within the NIS, each subject is coded by the ICD-9-CM diagnostic and procedure codes. The NIS comprises entirely de-identified patient data and is publicly available; therefore, institutional review board approval was not required for this study.

Data Extraction and Analysis

We included data on adults (age ≥ 18 years) who had undergone extracranial-intracranial (ECIC) cerebral bypass identified by the ICD-9-CM procedure code 39.28. Subjects were stratified on the basis of the year of treatment and/or clinical indication for cerebral bypass as defined by the ICD-9-CM code as follows: moyamoya disease (437.5), occlusive vascular disease (433.10, 433.11, 433.30, 434.90, and 434.91), and cerebral aneurysms (437.3 and 430). Extracted demographic information included age, sex, self-reported ethnicity, insurance status, severity of illness, and predicted risk of death based on the All Patient Refined Diagnosis Related Group (APR-DRG). Regional data were subdivided into Midwest, Northeast, South, and West. Inpatient complications were extracted and categorized on the basis of ICD-9-CM diagnostic codes. The ICD-9-CM diagnostic code 997.02 was used to identify iatrogenic cerebrovascular infarction or hemorrhage. Complication and mortality data were dichotomized as present or absent for subsequent data analysis. Cost was calculated from the total hospital charges and the year-specific, hospital-specific cost-to-charge ratio provided by the AHRQ [charge $\times$ (cost/charge ratio)] and was subsequently adjusted for inflation per the value of the US dollar for each year of analysis. Subjects with missing data in the aforementioned categories were excluded from analysis.

Statistical Analysis

Categorical and continuous variables are presented as proportions and means $\pm$ standard error, respectively, unless stated otherwise. National estimates were calculated using AHRQ sample weighting for each admission. Comparisons between groups were performed with Pearson's chi-square test for categorical variables and ANOVA for continuous variables. Multivariable logistic regression analysis was performed to identify statistically significant predictors of inpatient complications or death. Multivariable odds ratios and 95% confidence intervals were reported. Statistical significance was assessed at $p = 0.001$ to account for multiple comparisons. All statistical analyses were performed using the Statistical Package for the Social Sciences, version 25 (IBM Corp.).

Results

Patient Demographic and Clinical Characteristics

In total, 9065 subjects in the NIS underwent cerebral bypass after adjustment for AHRQ standard weights in the period from 2002 to 2014. The mean age of the bypass population was 42.7 ± 19.5 years, and there was a greater proportion of males (60.6%) and subjects who identified as white (62.5%). Indications for cerebral bypass included moyamoya disease (52.4%), occlusive vascular disease (30.7%), and cerebral aneurysm (16.9%). No subjects in the NIS underwent cerebral bypass for resection of neoplastic pathology. The overwhelming proportion of surgeries was performed at urban teaching hospitals (94.4%). For a summary of patient demographic and clinical characteristics, see Table 1.

Evolving Treatment Indications or Trends in Cerebral Bypass Surgery

From 2002 to 2014, there was an increase in the annual number of bypass surgeries performed in the US (Fig. 1A). Several noted changes in treatment indications for bypass were also identified. A growing proportion of cerebral bypass surgeries was performed for moyamoya disease with each year. Since 2005, moyamoya disease has been the leading indication for bypass across the nation (Fig. 1B). The trend also reflects a relative decline in the number of cases of occlusive vascular disease and cerebral aneurysms treated with cerebral bypass, which demonstrate different trajectories in their decline. With occlusive vascular disease, the number of bypass cases showed an abrupt decline in 2011, whereas bypass surgery for cerebral aneurysms has shown a more steady decline since 2002. For all years, a greater proportion of unruptured than ruptured aneurysms has been treated with bypass surgery (Fig. 1C).

Trends in Outcome and Mortality

Complications associated with hospitalization for bypass surgery initially declined prior to 2005 but have remained largely stable in more recent years (Fig. 2A). Rates of total, nonneurological, and neurological complications were 24.1%, 16.7%, and 7.4%, respectively. Rates of iatrogenic ischemic or hemorrhagic stroke following bypass were 3.8% for moyamoya disease, 4.9% for occlusive vas-

cular disease, and 20.4% for cerebral aneurysms (Table 2). When separated on the basis of treatment indication, rates of total or neurological complications and iatrogenic stroke showed no clear temporal trend (Fig. 2B–D). For each year, complications for cerebral bypass were disproportionately higher for the treatment of cerebral aneurysms (56.3%), and lowest for the treatment of moyamoya disease (13.2%; Table 2). Across bypass indications, the most prevalent inpatient complications included pulmonary (range 3.6%–30.4%), neurological (4.3%–22.5%), and renal/urinary (3.1%–14.8%). Multivariable logistic regression analysis confirmed that cerebral bypass for occlusive vascular disease (OR 1.7, 95% CI 1.4–2.0) or aneurysms (OR 2.9, 95% CI 2.4–3.4) has statistically higher odds for complications (Table 3). This analysis also identified advancing age (OR 1.02, 95% CI 1.01–1.02), major disease severity (OR 6.5, 95% CI 5.3–7.9), and major risk of death (OR 2.7, 95% CI 2.2–3.2) as statistically significant predictors for inpatient complications.

As with complications, inpatient mortality with cerebral bypass surgery was highest from 2002 to 2004. From 2005 onward, inpatient deaths declined 1.3- to 2.0-fold and remained largely stable until 2014 (Fig. 3A). This trend coincides with reduced mortality for cerebral aneurysms from 2002–2004 to 2005–2007. No clear longitudinal trend was observed in mortality rates with cerebral bypass for moyamoya disease. There was, however, a statistically significant increase in mortality with cerebral bypass for occlusive vascular disease in 2011–2014 compared to 2002–2007 ($p < 0.001$; Fig. 3B). The inpatient mortality rate for cerebral bypass was 1.9%. Mortality rates for bypass surgery were 0.3%, 1.4%, and 7.8% for moyamoya disease, occlusive vascular disease, and aneurysms, respectively. Multivariate logistic regression confirmed statistically higher odds of death with occlusive vascular disease (OR 4.3, 95% CI 2.1–8.9; Table 3) and aneurysm surgery (OR 7.5, 95% CI 3.9–14.5). Private insurance status (OR 3.3, 95% CI 1.9–5.8) and major risk of death (OR 4.0, 95% CI 2.4–6.8) also predicted greater statistical odds of death. Alternatively, an elective admission (OR 0.4, 95% CI 0.3–0.6) was associated with a statistically significant reduction in the odds of death.

Healthcare Costs Attributed to Cerebral Bypass

Despite the changing indications for cerebral bypass, mean hospital costs attributed to bypass surgery remained largely stable from 2002 to 2014 (Fig. 4A). Hospital costs attributed to bypass surgery remained relatively constant for each indication (Fig. 4B). However, mean costs varied across indications: moyamoya disease (\$38,406 $\pm$ \$483), vascular occlusive disease (\$46,618 $\pm$ \$774), and aneurysm (\$111,753 $\pm$ \$2381). The costs of bypass surgery are statistically significantly higher for the treatment of aneurysms than for moyamoya or vascular occlusive disease ($p < 0.001$). Much of this increased cost was driven by the treatment of ruptured aneurysms (unruptured \$87,464 $\pm$ \$2129 vs ruptured \$171,569 $\pm$ \$5377, $p < 0.001$).

Regional Variation

When the US was subdivided into four regions (Mid-

TABLE 1. Demographic and clinical characteristics of patients undergoing cerebral bypass in the US in 2002–2014

Characteristic	Value
Age in yrs	42.7 $\pm$ 19.5
Sex†	
M	5474 (60.6)
F	3561 (39.4)
Race*	
White	4457 (62.5)
African American	1048 (14.7)
Hispanic	532 (7.5)
Other	1098 (15.4)
Insurance	
Medicare	1661 (18.3)
Medicaid	1705 (18.8)
Private	4822 (53.2)
Other	877 (9.7)
Disease severity†	
Minor	2671 (29.6)
Moderate	3792 (42.0)
Major	1670 (18.5)
Extreme	901 (10.0)
Mortality risk†	
Minor	6026 (66.7)
Moderate	1416 (15.7)
Major	955 (10.6)
Extreme	638 (7.1)
Admission type†	
Nonelective	2419 (26.7)
Elective	6637 (73.3)
Disease type	
Moyamoya	4753 (52.4)
Occlusive vascular disease	2780 (30.7)
Cerebral aneurysm	1532 (16.9)
Medical center type†	
Rural	144 (1.6)
Urban nonteaching	362 (4.0)
Urban teaching	8539 (94.4)
Geographic region	
Northeast	1422 (15.7)
Midwest	2222 (24.5)
South	2447 (27.0)
West	2974 (32.8)
Mean total cost	\$53,523 $\pm$ 56712

Values expressed as the mean $\pm$ standard deviation or as number (%).

* Data not recorded for 1930 patients.

† The sum of the numbers per category may show slight variations from the overall sample size (9065) because of a small proportion of patients coded as “not applicable” for each category.

FIG. 1. **A:** Number of bypass procedures performed per 100,000 hospital admissions in the NIS from 2002 to 2014 in the US. Values expressed as mean $\pm$ standard deviation. **B:** Longitudinal trends in the proportion of cerebral bypass procedures performed for a given indication. **C:** Proportion of cerebral bypass procedures performed for the treatment of unruptured and ruptured aneurysms. Data normalized to total number of bypasses for aneurysms.

west, Northeast, South, and West), we noted that a lower number of bypass surgeries had been performed in the Northeast (Table 1 and Fig. 5A). Rates of bypass by indication were uniformly low in the Northeast (14%–17%; Fig. 5A). The relative proportions of bypass for each indication when stratified by region are presented in Fig. 5B. There was a trend for increased complications in the Midwest (26%) compared to the Northeast and the South (22%–23%; $p = 0.006$), whereas rates of neurological complications were statistically higher in the Northeast and West than in the South and Midwest (9%–10% vs 6%, $p < 0.001$). There were no statistically significant changes in mortality rates across regions (data not shown).

Discussion

The present report is the first to demonstrate national

trends for cerebral bypass surgery in the US in the modern endovascular era. Unlike institution-specific reports,³² the number of cerebral bypasses performed nationally according to the NIS database has increased from 2002 to 2014. This trend is explained by the increased utilization of bypass to treat moyamoya disease, which has become the leading national indication for cerebral bypass since 2005. The incidence of moyamoya disease in the US is estimated to be 0.57 cases per 100,000 person-years, but regional variability has been reported.^{5,27,29} Despite the disease's relative infrequency, the incidences of moyamoya diagnoses and hospitalizations have been rising in the US.²⁷ The source of this increase is unclear, and whether it represents a true rise in incidence or a growing awareness of the disorder or is reflective of improved imaging modalities is presently unknown. A number of authors in recent years have also suggested that direct revascularization may have

FIG. 2. Longitudinal trend (A) in total inpatient complication rate for cerebral bypass surgery from 2002 to 2014 in the US. Graph showing total complication rate (B), neurological complications rate (C), and rate of iatrogenic stroke (D), stratified by indication for cerebral bypass.

TABLE 2. Inpatient complication rates for cerebral bypass surgery in 2002–2014

Complication	Moyamoya (n = 4753)	Occlusive (n = 2780)	Aneurysm (n = 1532)	Total (n = 9065)
Any complication	626 (13.2%)	699 (25.1%)	862 (56.3%)	2187 (24.1%)
Iatrogenic stroke	180 (3.8%)	136 (4.9%)	312 (20.4%)	628 (6.9%)
All neurological	206 (4.3%)	161 (5.8%)	345 (22.5%)	674 (7.4%)
Other bleeding events	44 (0.9%)	98 (3.5%)	97 (6.3%)	239 (2.6%)
Pulmonary	170 (3.6%)	191 (6.9%)	466 (30.4%)	787 (8.7%)
Cardiac	30 (0.6%)	86 (3.1%)	76 (5.0%)	191 (2.1%)
Thromboembolic*	40 (0.8%)	64 (2.3%)	160 (10.4%)	252 (2.8%)
Renal/urinary	148 (3.1%)	244 (8.8%)	226 (14.8%)	602 (6.6%)
Infection	9 (0.2%)	39 (1.4%)	58 (3.8%)	106 (1.2%)
Iatrogenic puncture	32 (0.7%)	5 (0.2%)	49 (3.2%)	81 (0.9%)
Anemia	127 (2.7%)	134 (4.8%)	158 (10.3%)	414 (4.6%)
Gastrointestinal	15 (0.3%)	0 (0.0%)	0 (0.0%)	15 (0.2%)
Other procedural	5 (0.1%)	10 (0.3%)	15 (1.0%)	25 (0.3%)

n = number of cases.

* Thromboembolic complications included deep venous thromboses and pulmonary emboli.

added benefit in stroke prevention in adult moyamoya disease,^{12,17,19} and the upward trend in bypass for moyamoya may also suggest that a larger proportion of the disease is being treated with ECIC bypass in lieu of other treatment options in the US. Whether treatment biases are changing is presently unknown. Although limited in outcome metrics, our data indicate that cerebral bypass in appropriately selected moyamoya patients is associated with a low risk of complications or death, especially compared to the rates for other bypass indications.

The rise in surgical revascularization for moyamoya has outpaced the relative decline in bypasses for other indications such as other occlusive vascular lesions or cerebral aneurysms. For occlusive vascular disease, the number of bypasses declined abruptly after 2010, coinciding with the release of the COSS results, which indicated no risk reduction in recurrent stroke with ECIC bypass for the treatment of atherosclerotic internal carotid artery occlusion.²⁵ Our findings may suggest that the COSS findings have been influential in shaping bypass indications and have been widely implemented in clinical practice. In the COSS, the rate of periprocedural stroke was 15.0% and 12.9% within 30 or 2 days of the bypass procedure, respectively.^{13,25} In the present report, we found a 4.9% rate of iatrogenic stroke following cerebral bypass for vascular occlusive disease. The source of this discrepancy in rates is unclear. It may reflect retrospective coding errors or omissions in the NIS. In addition, the COSS included only those patients with symptomatic internal carotid occlusions defined on vascular imaging, and all participants underwent extensive clinical testing to detect stroke postprocedurally.^{13,25} Therefore, it is likely that there were discrepancies in disease severity and/or the sensitivity of postoperative monitoring outside a tightly controlled clinical trial, which limit the comparability of the COSS and the present report. We noted statistically increased mortality with cerebral bypass post-2011. We hypothesize that this reflects a potential selection bias and that bypass for occlusive vascular disease is now being considered a treat-

ment of last resort and reserved for severe complication-prone cases refractory to other treatment modalities. However, future studies are required to confirm this trend in cerebral bypass for vascular occlusion and better characterize select subpopulations, e.g., those refractory to other treatment modalities, in which revascularization may still play a role.

Unlike with occlusive vascular disease, national trends in bypass utilization for the treatment of cerebral aneurysms demonstrate a more gradual decline from 2002 without a clear inflection point. Aneurysms conventionally treated with surgical bypass were those not amenable to either clipping or coiling. Many of these aneurysms were giant in size (> 2.5 cm), fusiform or dolichoectatic, partially thrombosed, or incorporating eloquent arterial perforators or branches that could not be safely sacrificed. With the development of flow-diverting stents, such as the Pipeline embolization device (PED), many of these aneurysms can now be treated endovascularly.^{8,24} Estimates suggest that nearly 50% of all aneurysms can be treated with flow diversion—a statistic that highly varies based on aneurysm location within the cerebral circulation.⁷ Despite FDA approval of the PED in 2011, there is no corresponding inflection point in trends of bypass utilization. Whether this reflects off-label PED use prior to FDA approval, the utilization of other endovascular technology, or the fact that flow diversion is not the therapeutic panacea it was once thought remains to be determined.²³

Even with the continued evolution of technology, bypass remains uniquely suited for complex and/or fusiform aneurysms in certain regions of the cerebral circulation including the middle cerebral artery, posterior inferior cerebellar arteries, or more distal cerebral arterial branches.^{1,2,14,15,28} Cerebral aneurysms remain a leading indication for bypass at some centers,^{14,15} and bypass will likely remain an important treatment option for aneurysms not amenable to endovascular therapy or open surgical clipping. However, our data suggest that cerebral bypass for aneurysms is associated with a comparatively higher rate

TABLE 3. Multivariable logistic regression analysis of predictors of inpatient complications and death following cerebral bypass in the US

Parameter	Inpatient Complications		Inpatient Death	
	OR (95% CI)	p Value	OR (95% CI)	p Value
Primary diagnosis (vs moyamoya)		<0.001		<0.001
Intracranial occlusion/stenosis	1.7 (1.4–2.0)	<0.001	4.3 (2.1–8.9)	<0.001
Aneurysm	2.9 (2.4–3.4)	<0.001	7.5 (3.9–14.5)	<0.001
Age, per-yr increase	1.02 (1.01–1.02)	0.001	1.00 (0.99–1.01)	0.982
Sex (vs male)		0.003		0.003
Female	1.2 (1.1–1.4)		1.9 (1.2–2.9)	
Race (vs white)		0.004		0.063
African American	1.2 (1.0–1.5)	0.068	0.3 (0.1–0.7)	0.009
Hispanic	0.9 (0.7–1.2)	0.364	1.3 (0.7–2.6)	0.406
Asian	1.2 (0.9–1.7)	0.147	1.4 (0.6–3.2)	0.410
Other/unknown	1.3 (1.1–1.5)	0.001	—	—
Insurance (vs Medicare)		0.010		<0.001
Medicaid	1.0 (0.8–1.2)	0.954	1.0 (0.5–2.0)	0.943
Private	1.2 (1.0–1.4)	0.039	3.3 (1.9–5.8)	<0.001
Other	1.4 (1.1–1.9)	0.008	2.1 (0.9–4.5)	0.068
Severity of disease (vs moderate)		<0.001		—
Minor	0.2 (0.1–0.2)	<0.001	—	—
Major/extreme	6.5 (5.3–7.9)	<0.001	—	—
Risk of death (vs moderate)		<0.001		<0.001
Minor	1.1 (0.9–1.3)	0.540	—	—
Major/extreme	2.7 (2.2–3.2)	<0.001	4.0 (2.4–6.8)	<0.001
Type of admission (vs non-elective)		0.010		<0.001
Elective	1.2 (1.0–1.4)		0.4 (0.3–0.6)	
Bed size (vs small)		0.828		0.973
Medium	1.0 (0.7–1.3)	0.956	1.1 (0.4–3.1)	0.819
Large	1.0 (0.8–1.3)	0.717	1.1 (0.5–2.2)	0.897
Type of medical center (vs non-teaching)		0.010		0.437
Teaching	1.5 (1.1–1.9)		1.6 (0.5–4.9)	
Geographic region (vs Northeast)		0.034		0.299
Midwest	0.7 (0.6–0.9)	0.005	1.8 (0.9–3.6)	0.086
South	0.8 (0.7–1.0)	0.102	1.2 (0.6–2.3)	0.617
West	0.9 (0.7–1.1)	0.257	1.4 (0.7–2.7)	0.340

Boldface type indicates statistical significance for main categories.

FIG. 3. A: Mortality rate for cerebral bypass surgery from 2002 to 2014. **B:** Graph showing longitudinal trend in the mortality rate stratified by indication for cerebral bypass.

FIG. 4. A: Mean cost for cerebral bypass surgery in the US from 2002 to 2014. **B:** Graph showing longitudinal trends in mean cost per hospitalization for bypass surgery stratified by indication for cerebral bypass. USD = US dollars.

of complications, including iatrogenic stroke and death. These findings stress the importance of careful patient selection and the reservation of bypass surgery for aneurysms that cannot be treated safely with other therapeutic modalities. With the surgical treatment of aneurysms, studies have shown that the outcome is better when the patient is treated at a medical center with higher case volumes,^{4,9,11} and lower rates of periprocedural stroke have been reported at higher-volume centers.^{14,15,28,32} Therefore, complex aneurysms requiring cerebral bypass should be referred to regional centers of excellence with multidisciplinary neurocritical care and experienced dual-trained cerebrovascular neurosurgeons.

Despite an initial decline in complications and death between 2002–2004 and 2005–2007—a trend largely driven by improved safety in bypass surgery for cerebral aneurysms—rates of inpatient death and complications have remained stable. In addition to neurological consequences, our results highlight a relatively high rate of pulmonary and renal complications. This stresses the importance of minimizing ventilation days and using aggressive pulmonary hygiene and fluid management whenever possible. Rates of neurological complications and iatrogenic stroke have also stagnated. Whether the majority of neurological complications are ischemic in nature in this data set is unclear, and the NIS does not have sufficient granularity to analyze this factor in greater detail. Adoption of new techniques to ensure intraoperative graft patency, such as indocyanine green angiography, have been successful,^{26,33} and graft patency exceeds 90% in large, contemporary clinical series.^{13,36} However, technical innovations in bypass surgery to decrease

ischemic complications have been comparatively minimal. Attempts to develop technologies with little to no ischemia time, such as the vascular couplers and the excimer laser-assisted nonocclusive anastomosis (ELANA) device or automated anastomotic devices, have been largely unsuccessful or failed to gain widespread acceptance.^{6,10,30,31} Our data support continued interest and investment in the development of new technologies and/or approaches to further reduce neurological complications and improve patient outcomes. Efforts dedicated to refining surgical technique is required by practicing cerebrovascular neurosurgeons, and adequate exposure and training must be provided to neurosurgical trainees to perfect microsurgical anastomosis.^{20,21} Continued evaluation of bypass indications is also needed to further refine patient selection, especially with the evolution of newer bypass techniques.¹⁸

Study Limitations

Our results reflect national trends in cerebral bypass, but this study is not without limitations. Our findings are based on analysis of a single administrative database and should be viewed as preliminary until replicated in other national data sets. The NIS is one of the largest all-payer inpatient databases in the US and is representative of the general population. However, it is comprised of information extracted from hospital discharge summaries, which may be prone to coding errors. The NIS is also based on the ICD-9-CM codes, and coding for different bypass procedures was limited. The trends described here are limited to ECIC bypass and cannot be extended to intracranial-

FIG. 5. A: Regional variation and longitudinal trend in proportion of cerebral bypasses performed in US. **B:** Geographic variability in indications for cerebral bypass across the US.

intracranial or indirect bypass procedures such as encephaloduroarteriosynangiosis or encephalomyosynangiosis. With respect to complication data, the NIS does not allow one to determine complications directly attributable to the bypass procedure or those incurred either prior to the procedure or during a prolonged hospitalization and unrelated to the procedure. As a result, it is not possible to state that the reported complication rates reflect entirely procedure-related complications and thus likely overestimate the rates of complication for cerebral bypass surgery. Neither is it possible to declare whether a recorded complication was clinically significant or influenced a patient's hospitalization. The NIS also lacks sufficient granularity in the outcome data collected, and our analysis is limited to inpatient complications and mortality.

Conclusions

Cerebral bypass surgeries for adult revascularization have increased in the US from 2002 to 2014. The rising rates of bypass are driven by a greater proportion of surgeries performed for moyamoya disease, whereas cases for vascular occlusive disease and aneurysms are decreasing. Importantly, cerebral bypass remains an important surgical tool in the armamentarium of cerebrovascular neurosurgeons in the modern endovascular era, stressing the importance of maintaining microsurgical skills in trainees and early-career neurosurgeons. Despite refining treatment indications, rates of periprocedural stroke and complications have stagnated, highlighting the need for continued interest and investment in evolving available bypass techniques or technologies to improve patient outcome.

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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: Abula, Winkler, Rodriguez Rubio, Burkhardt. Acquisition of data: Winkler, Yue, Deng, Phelps, Rutledge, Lu. Analysis and interpretation of data: Winkler, Burkhardt. Drafting the article: Winkler, Phelps, Lu. Critically revising the article: Abula, Raygor, Rutledge, Rodriguez Rubio. Reviewed submitted version of manuscript: Raygor. Statistical analysis: Yue, Deng.

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