Early Readmission After Ventricular Shunting in Adults with Hydrocephalus: A Nationwide Readmission Database Analysis

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■ BACKGROUND: **Ventricular shunting is one of the primary modalities for addressing hydrocephalus in both children and adults. Despite advances in shunt technology and surgical practices, shunt failure is a persistent challenge for neurosurgeons, and shunt revisions account for a substantial proportion of all shunt-related procedures. There are a wealth of studies elucidating failure patterns and patient demographics in pediatric cohorts; however, data in adults are less uniform. We sought to determine the rates of all-cause and shunt failure readmission in adults who underwent the insertion of a ventricular shunt.**

■ METHODS: **We queried the Nationwide Readmissions Database from 2010 to 2014 to evaluate new ventricular shunts placed in adults with hydrocephalus. We sought to determine the rates of all-cause and shunt revision-related readmissions and to characterize factors associated with readmissions. We analyzed predictors including patient demographics, hospital characteristics, shunt type, and hydrocephalus cause.**

■ RESULTS: **Analysis included 24,492 initial admissions for shunt placement in patients with hydrocephalus. Of patients, 9.17% required a shunt revision within the first 6 months; half of all revisions occurred within the first 41 days. There were 4044 (16.50%) 30-day and 5758 (28.8%) 90-day all-cause readmissions. In multivariable analysis, patients with a ventriculopleural shunt, Medicare insurance, and younger age had increased likelihood for shunt revision. Notable predictors for all-cause readmission were insurance type, length of hospitalization, age, comorbidities, and hydrocephalus cause.**

■ CONCLUSIONS: **Most shunt revisions occurred during the first 2 months. Readmissions occurred frequently. We identified patient factors that were associated with all-cause and shunt failure readmissions.**

INTRODUCTION

Hydrocephalus refers to a perturbation in the normal homeostasis of cerebrospinal fluid (CSF) production, circulation, or reabsorption, culminating in increased intracranial pressure.[1] The literature is replete with studies detailing disease incidence and hospitalization trends in children with hydrocephalus.[2-7] In contrast, limited data are available for adults. Although little distinction is made between pediatric and adult-onset hydrocephalus in many studies, the pathophysiologic basis for the disease is fundamentally distinct in these 2 age-groups. Whereas pediatric hydrocephalus is largely consequent to congenital defects in CSF pathways, adult hydrocephalus generally develops in the wake of diseases such as intracerebral hemorrhage (ICH), tumor, infection, trauma, and idiopathic normal pressure hydrocephalus (NPH), among others.

Key words
- Adult cohort
- Hydrocephalus
- Nationwide database
- Readmission
- Shunt failure
- Shunt revision
- Ventricular shunt

Abbreviations and Acronyms
CI: Confidence interval
CSF: Cerebrospinal fluid
ICD-9-CM: *International Classification of Diseases, Ninth Revision, Clinical Modification*
ICH: Intracerebral hemorrhage
NPH: Normal pressure hydrocephalus
NRD: Nationwide Readmissions Database
OR: Odds ratio
VP: Ventriculoperitoneal

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Ventricular shunt placement is a definitive surgical treatment for adult hydrocephalus. Shunting decreases hydrocephalus-related complications, but is not without its own morbidity because patients may require 1 or more revisions over the course of their lifetime. Shunt revision rates in pediatric cohorts are well described, ranging from 44% to 81%.[2-7] However, failure patterns in adults are not so well characterized. Failure rates in adults are generally lower (17%–33%)[7-15] and predominantly reflect revisions within the first 6 months after insertion. Single-institution analyses suggest that 9.1%–26% of adults required revision during the first 6 months,[7-15] whereas the 2 state-based data sets suggest a 15%–21% 1-year adult revision rate.[7,11] We seek to derive an estimate of shunt failure using a large cohort of adults with hydrocephalus via the Nationwide Readmissions Database (NRD).

Hospital readmission rates have been directly correlated to various quality metrics and in-hospital mortality.[16,17] They have become the focus of policy makers, hospital administrators, and third-party payers, not only because of their use as litmus tests for health care quality but because of their enormous fiscal footprint. The Hospital Readmissions Reduction Program was established in 2012 under the Affordable Care Act for improving health care quality by penalizing institutions having suboptimal care based on excessive hospital readmissions. Because hydrocephalus remains a common clinical entity encountered by neurosurgeons and half of all shunt-related surgeries necessitate readmission for revision,[18] identifying potentially modifiable patient-related and hospital-related factors that contribute to readmission after hydrocephalus treatment could improve the quality of care and reduce health care costs.

The NRD is a pooled database of hospital admissions across 20–27 states in which patients are tracked using de-identified linkage numbers. It is unique from other national samples (e.g., Nationwide Inpatient Sample) because it is not limited to cross-sectional analysis of hospitalizations within a defined period. In readmission analysis, a particular diagnosis and/or procedure during an admission is defined as an index admission. Patients with an index admission are followed for the calendar year for subsequent readmissions. We can report the rate of occurrence of procedures and/or diagnoses during those readmissions and evaluate the time-to-event (e.g., readmission or subsequent procedures) associated with individual patients. Patients shunted for hydrocephalus are therefore a suitable cohort to analyze using the NRD because the risk of shunt failure and related complications is generally highest in the immediate months after treatment.

The goals of this study were 1) to determine a shunt failure rate at 6 months, 2) to analyze readmission trends for shunted hydrocephalus, and 3) to characterize patient or hospital factors that affect readmission or shunt revision.

METHODS

Data Source

We included the 2010–2014 data sets of the NRD. The NRD has been previously described[19] and can be purchased by the general public from the Healthcare Cost and Utilization Project of the Agency for Healthcare Research and Quality, part of the U.S. Department of Health and Human Services. The purpose of the NRD is to combine state inpatient discharge databases to permit larger-scale analyses. Each patient discharged is assigned a unique linkage number, permitting them to be tracked for readmission during that year.

Study Population

Adults ≥19 years of age with an admission procedure of initial insertion of ventricular shunt (*International Classification of Diseases, Ninth Revision, Clinical Modification* [ICD-9-CM] procedure code 2.3x) and a diagnosis of hydrocephalus (ICD-9-CM diagnosis codes 331.3–5, 741.x, 742.3) were included. ICD-9-CM procedure codes for ventriculoperitoneal (VP) shunt placement 2.33 and 2.34 have been validated in an institutional retrospective chart review.[20] Patients who had an index admission containing other shunt procedures, including shunt revisions (2.41–42, 54.95), patients who died, and patients with missing data of survival, length of stay, or time to procedures were excluded. The index admission was the first admission at which an initial shunt was placed. Readmissions were dichotomized into all-cause and shunt revision (admissions that included any ICD-9 code of new shunt placement, shunt revision). Because the NRD collects data only for a calendar year, patients with insufficient length of follow-up for each analysis were excluded.

The schematic of our study design is presented in **Figure 1**.

Patient and Hospital Characteristics

The NRD consists of a standard set of variables previously described[19] and available at https://www.hcup-us.ahrq.gov/db/nation/nrd/nrddde.jsp. The data set consists of patient, hospital, and admission variables, which are reproduced later for completeness. We analyzed patient variables such as insurance type (Medicaid, Medicare, no charge, other, privately insured, and self-pay), gender, and urban versus rural location. We categorized patient age as in previous analyses using the following cut points: 19–44, 45–64, 65–74, and ≥75 years old.[19] The Elixhauser Comorbidity Index[21] is a set of 30 comprehensive measures of medical comorbidity that has been extensively validated in different populations and is available in the NRD.[22] We dichotomized Elixhauser comorbidities into the presence or absence of ≥1 comorbidity. We evaluated variables including hydrocephalus diagnosis category, type of initial shunt placement (2.31–2.39), presence of intracranial trauma (ICD-9 800.00–802.99, 850.00–854.99), presence of intracranial hemorrhage (ICD-9 430.00–432.99), NPH (331.5), obesity (278.0 or V85.3 or V85.4), extracranial infection (001.00–139.99, 995.91-92), intracranial infection (320.00–326.99), cranial tumor (140.00–239.99), craniotomy (ICD-9 procedure 01.00–01.99), length of stay (≤14 days vs. >14 days). We also evaluated hospital-level NRD variables including size, teaching or nonteaching status, and annual hospital shunt procedure volume. Bed size and teaching status are reported as categories based on hospitals in a similar geographic region and urban/rural setting. Shunt procedure volume was calculated and hospitals at or above the 90th percentile per year for shunts (32 shunts/year) were labeled as high volume. Data regarding total charges from each admission were provided in dollars in the NRD. These charges reflect total hospital billing but not professional fees and range from $100 to $1.5 million in 2010 and from $100 to $5 million in 2011–2014.

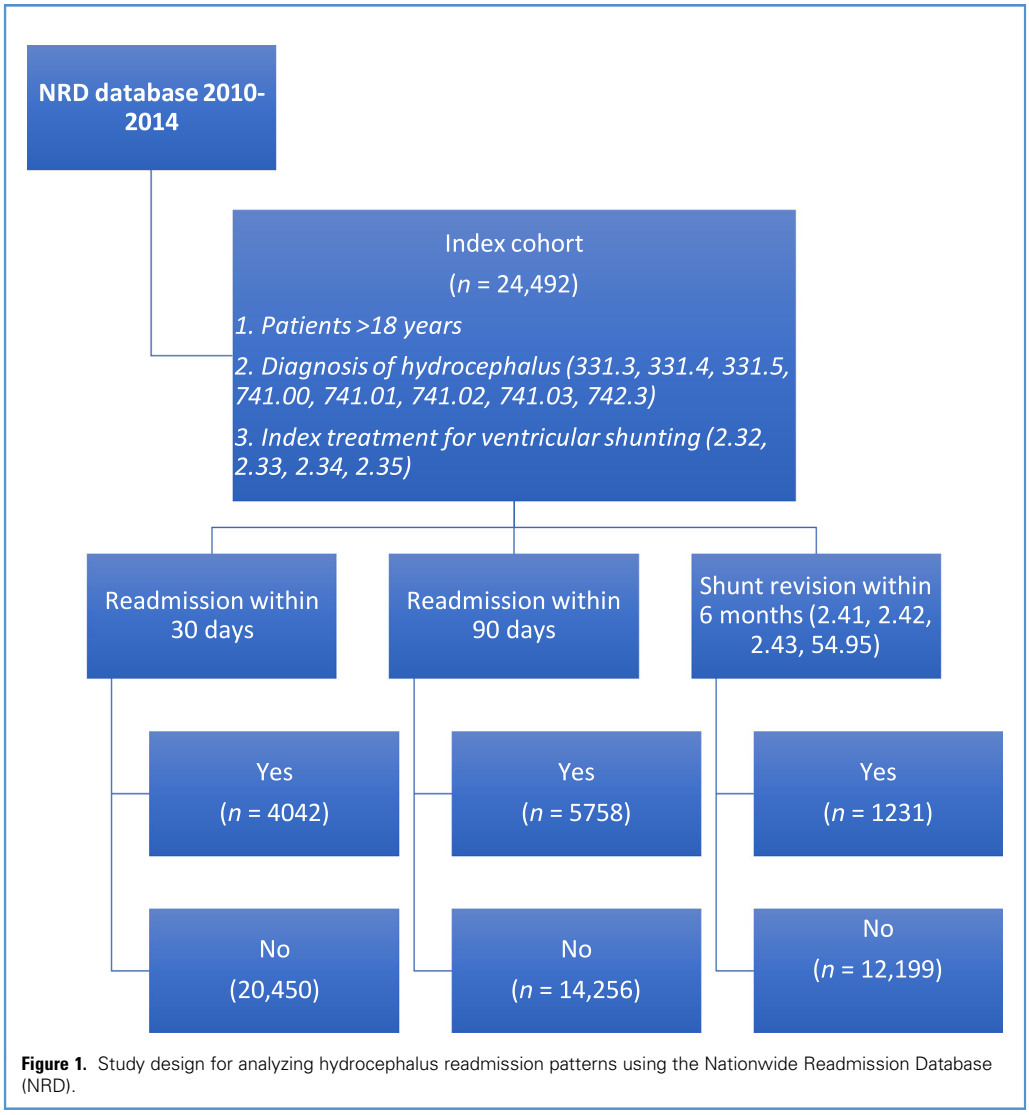

Figure 1. Study design for analyzing hydrocephalus readmission patterns using the Nationwide Readmission Database (NRD).

Statistical Analysis

Our primary outcomes were 30-day and 90-day all-cause readmission and 6-month shunt revision readmission rate. We did not include further readmissions beyond the first readmission recorded. Logistic regression was used for multivariable analyses. The results of our regression analysis are described by odds ratios (OR) and 95% confidence intervals (CIs). A Kaplan-Meier curve is used for the readmission figure.

We used the SAS 9.4 software package (SAS Institute Inc., Cary, North Carolina, USA). Significance levels were defined as $P < 0.05$.

RESULTS

Patient and Hospital Baseline Characteristics

Between 2010 and 2014, we included 24,492 index admissions for hydrocephalus receiving ventricular shunting in the NRD database. The median length of stay was 5 days and the median cost of hospitalization was $66,792. Adult patients were divided into 4 age cohorts for the purposes of analysis: 19–44 (16%), 45–64 (28.9%), 65–74 (24.7%), and ≥75 years (30.4%). Aside from the youngest group, there was roughly even distribution among subsets. Gender was also equally distributed: males (50.5%, n = 12,378), females (49.5%, n = 12,114).

Most patients (77%, n = 18,853) within the index population had ≥1 baseline comorbidities. Most patients had Medicare (56.6%, n = 13,859) or private insurance (26.5%, n = 6,492) and were treated at major metropolitan teaching hospitals (76%, n = 18,627) with large bed size (79.5%, n = 19,477). Among those treated, obstructive hydrocephalus (45.2%, n = 11,079) and idiopathic NPH (38.2%, n = 9359) were the most common reasons for shunt placement. VP shunting was the most common modality used for treatment (97.4%, n = 23,861).

Readmission Demographics

Within 30 days of discharge from index hospitalization, there were 4042 readmissions (16.5%) and within 90 days of discharge there

Table 1. Most Frequently Charted Primary Diagnoses on Readmission

International Classification of Diseases, Ninth Revision Code	Diagnosis	Frequency (% readmission)	
		30-day	90-day
5990	Urinary tract infection, site not specified	895 (22.14)	1238 (21.50)
9962	Mechanical complication of nervous system device, implant, and graft	488 (12.07)	701 (12.17)
34590	Epilepsy, unspecified, without mention of intractable epilepsy	407 (10.07)	609 (10.58)
5849	Acute kidney failure, unspecified	351 (8.68)	451 (7.83)
34830	Encephalopathy, unspecified	298 (7.37)	375 (6.51)
4321	Subdural hemorrhage	293 (7.25)	501 (8.70)
99663	Infection and inflammatory reaction caused by nervous system device, implant, and graft	270 (6.68)	331 (5.75)
99591	Sepsis	262 (6.48)	348 (6.04)
3485	Cerebral edema	258 (6.38)	328 (5.70)
486	Pneumonia, organism unspecified	249 (6.16)	339 (5.89)

were 5758 readmissions (28.8% of patients with 90-day follow-up). The median time to readmission within 30 days was 11 days and the median readmission cost $39,401. The median time to readmission within 90 days was 25 days and the median readmission cost $40,019.

The 3 most common primary diagnoses specified on readmission at 30 and 90 days were urinary tract infection (*ICD-9* diagnosis code 599.0), mechanical complication of nervous system device (*ICD-9* diagnosis code 996.2), and seizures (*ICD-9* diagnosis code 34590). See **Table 1** for a listing of other common readmission diagnoses charted.

Factors Associated with 30-Day Readmission

Key demographics for patients readmitted within 30 days are listed in **Table 2**. Hospital teaching status and procedure volume were not significantly associated with 30-day readmission. However, several factors had notable associations. Those with Medicare insurance (OR, 1.17; $P = 0.01$) and $\geq$1 comorbidities (OR, 1.17; $P < 0.001$) were more likely to be readmitted within 30 days. Younger age, particularly 18–44 years, was associated with a higher likelihood for readmission (OR, 1.24; $P < 0.01$). Patients with a diagnosis of intracranial tumor (OR, 1.62; $P < 0.0001$) or extracranial infection (OR, 1.35; $P < 0.0001$) on index admission were more likely to return by 30 days.

Contrastingly, female patients had lower odds for readmission compared with their male counterparts (OR, 0.86; $P < 0.0001$). In like manner, patients treated for congenital hydrocephalus (whether communicating or noncommunicating), idiopathic NPH, and communicating hydrocephalus were less likely to be readmitted within 30 days compared with patients with noncommunicating hydrocephalus: OR, 0.67, $P = 0.03$, OR, 0.64, $P < 0.0001$, and OR, 0.83, $P < 0.01$, respectively. Those shunted for hydrocephalus in the context of hemorrhage (OR, 0.85; $P < 0.010$) also had a lower likelihood for readmission (**Table 3**).

Factors Associated with 90-Day Readmission

Demographics for patients readmitted within 90 days and associated predictors of readmission are listed in **Tables 4** and **5**. Similar to all-cause readmission at 30 days, those with Medicare insurance (OR, 1.23; $P < 0.001$), $\geq$1 comorbid conditions (OR, 1.09; $P = 0.03$), and a concomitant diagnosis of tumor (OR, 1.60; $P < 0.0001$) or extracranial infection (OR, 1.40; $P < 0.0001$) had higher odds of readmission within 90 days. Although no significant association was noted at 30 days, patients with traumatic brain injury (OR, 1.28; $P = 0.02$) were more likely to be readmitted within 90 days. Again, female gender (OR, 0.89; $P < 0.001$), communicating hydrocephalus (OR, 0.85; $P = 0.0023$), and idiopathic NPH (OR, 0.69; $P < 0.0001$) were associated with decreased likelihood of admission. Likewise, elderly patients aged 65–74 years had lower likelihood for readmission within 90 days (OR, 0.87; $P < 0.01$).

Six-Month Shunt Failure Rates

Of the 13,430 patients tracked for readmission over 6 months, 9.17% ($n = 1231$) underwent shunt revision. The median time to shunt revision was 41 days, and a survival curve is shown in **Figure 2**. Of shunts revised, 47.93% ($n = 590$) had a diagnosis of mechanical shunt complication (*ICD-9* code 996.2), 22.75% ($n = 280$) had a diagnosis of shunt infection (*ICD-9* code 99.663), and 14.38% ($n = 177$) had a diagnosis of nontraumatic subdural hemorrhage (*ICD-9* code 432.1), suggesting overdrainage. The overall obstruction rate 6 months after placement was 4.39% (590/13430). The overall infection rate was 2.08% (280/13430). The overall overdrainage rate was 1.32% (177/13430).

Factors Associated with Shunt Revision at 6 Months

In the 1231 patients who required a shunt revision within 6 months of placement, obstructive hydrocephalus was the most common form of hydrocephalus requiring revision (50.12%, $n = 617$), followed by idiopathic NPH (30.22%, $n = 372$) and communicating

Table 2. Demographics of Patients Readmitted within 30 Days of Index Hospitalization

Variables	N	%
Diagnosis		
Communicating hydrocephalus (331.3)	485	12.0
Obstructive hydrocephalus (331.4)	2253	55.7
Idiopathic normal pressure hydrocephalus (331.5)	1145	28.3
Spina bifida—related hydrocephalus (741.XX)	23	0.6
Congenital hydrocephalus (742.3)	221	1.1
Multiple diagnoses	597	2.9
Total	4042	16.5
Procedure		
Ventriculoatrial shunt (2.32)	45	1.1
Ventriculopleural shunt (2.33)	57	1.4
Ventriculoperitoneal shunt (2.34)	19922	97.4
Multiple procedures	DS*	
Age		
18.1—44 years	787	19.5
45—64 years	1269	31.4
65—74 years	954	23.6
≥75 years	1032	25.5
Gender		
Male	2117	52.4
Female	1925	47.6
Primary insurance		
Medicare	2118	52.5
Medicaid	543	13.5
Private insurance	1145	28.4
Self-pay	107	2.7
No charge	16	0.4
Other	102	2.5
Hospital bed size		
Small	189	4.7
Medium	595	14.7
Large	3258	80.6
Teaching status		
Metropolitan nonteaching	47	1.2
Metropolitan teaching	3077	76.1
Nonmetropolitan hospital	918	22.7
Elixhauser comorbidity		
Any one present	3168	78.4
None	874	21.6
Volume		
>90th percentile	1758	43.5
≤90th percentile (32/year)	2284	56.5
Trauma		
Presence of any traumatic brain injury	122	3.0
None	3920	97.0
Hemorrhage		
Presence any of subarachnoid hemorrhage intracerebral hemorrhage	753	18.6
None	3289	81.4
Normal pressure hydrocephalus		
Yes	1205	29.8
No	2837	70.2
Extracranial infection		
Yes	903	22.3
No	3139	77.7
Intracranial infection		
Yes	234	5.8
No	3808	94.2
Tumor		
Yes	1044	25.8
No	2998	74.2
Craniotomy		
Yes	728	18.0
No	3314	82.0
Length of stay		
>14 days	1402	34.7
≤14 days	2640	65.3

*DS = data suppressed according to Healthcare Cost and Utilization Project/Nationwide Readmissions Database regulations.

causes (12.75%, n = 157) (Table 6). Age was inversely correlated with likelihood for shunt revision, with younger patients aged 18—44 years having more than twice the odds compared with those ≥75 years (OR, 2.28; $P < 0.0001$). Other notable predictors for shunt revision include patients with a ventriculopleural device (OR, 1.95; $P = 0.004$). Those with

Table 3. Predictors of 30-Day All-Cause Readmissions by Multivariate Analysis Using Survey-Adjusted Logistic Regression

Variables	Odds Ratio	95% Confidence Interval		*P* Value
Gender				
Female	0.862	0.804	0.923	<0.0001
Male	Reference			
Primary insurance				
Medicare	1.167	1.032	1.32	0.0138
Medicaid	1.109	0.986	1.248	0.0847
Self-pay	0.847	0.674	1.064	0.154
No charge	1.439	0.835	2.479	0.1901
Other	0.847	0.673	1.065	0.1548
Private insurance	Reference			
Age				
18.1—44 years	1.241	1.058	1.456	0.0079
45—64 years	1.076	0.937	1.235	0.3003
65—74 years	1.031	0.935	1.136	0.539
≥75 years	Reference			
Elixhauser comorbidity				
Any one present	1.167	1.069	1.274	0.0006
None	Reference			
Diagnosis category				
Communicating hydrocephalus (331.3)	0.829	0.738	0.931	0.0016
Idiopathic normal pressure hydrocephalus (331.5)	0.637	0.573	0.708	<0.0001
Spina bifida—related hydrocephalus (741.xx)	0.92	0.59	1.433	0.7111
Congenital hydrocephalus (742.3)	0.671	0.468	0.962	0.03
Multiple diagnoses	0.665	0.528	0.838	0.0005
Obstructive hydrocephalus (331.4)	Reference			
Hemorrhage				
Presence any of subarachnoid hemorrhage intracerebral hemorrhage	0.849	0.76	0.949	0.0041
None	Reference			
Extracranial infection				
Yes	1.35	1.23	1.482	<0.0001
No	Reference			
Tumor				
Yes	1.615	1.472	1.772	<0.0001
No	Reference			
Length of stay				
>14 days	1.143	1.038	1.259	0.0066
≤14 days	Reference			

hemorrhage-related hydrocephalus were less likely to undergo revision (OR, 0.66; $P < 0.0001$). Patient gender, hospital volume, hospital teaching status, and type of hydrocephalus had no impact on shunt revision rates (Table 7). Table 8 describes the most frequently coded procedures during readmission for shunt revision within 6 months.

Table 4. Demographics of Patients Readmitted within 90 days of Index Hospitalization

Variables	N	%
Diagnosis		
Communicating hydrocephalus (331.3)	687	11.9
Obstructive hydrocephalus (331.4)	3052	53.0
Idiopathic normal pressure hydrocephalus (331.5)	1772	30.8
Spina bifida—related hydrocephalus (741.XX)	29	0.5
Congenital hydrocephalus (742.3)	48	0.8
Multiple diagnoses	170	3.0
Total	5758	28.8
Procedure		
Ventriculoatrial shunt (2.32)	79	1.4
Ventriculopleural shunt (2.33)	75	1.3
Ventriculoperitoneal shunt (2.34)	5603	97.3
Multiple procedures	DS*	
Age		
18.1—44 years	1069	18.6
45—64 years	1778	30.9
65—74 years	1289	22.4
≥75 years	1622	28.2
Gender		
Male	2998	52.1
Female	2760	47.9
Primary insurance		
Medicare	3106	53.9
Medicaid	732	12.7
Private insurance	1592	27.7
Self-pay	150	2.6
No charge	21	0.4
Other	145	2.5
Hospital bed size		
Small	289	5.0
Medium	858	14.9
Large	4611	80.1
Teaching status		
Metropolitan nonteaching	66	1.2
Metropolitan teaching	4384	76.1
Nonmetropolitan hospital	1308	22.7
Elixhauser comorbidity		
Any one present	4470	77.6
None	1288	22.4
Volume		
>90th percentile	2487	43.2
≤90th percentile (32/year)	3271	56.8
Trauma		
Present any of traumatic brain injury	163	2.8
None	5595	97.2
Hemorrhage		
Presence of any of subarachnoid hemorrhage intracerebral hemorrhage	1063	18.5
None	4695	81.5
Normal pressure hydrocephalus		
Yes	1871	32.5
No	3887	67.5
Extracranial infection		
Yes	1236	21.5
No	4522	78.5
Intracranial infection		
Yes	316	5.5
No	5442	94.5
Tumor		
Yes	1379	24.0
No	4379	76.1
Craniotomy		
Yes	987	17.1
No	4771	82.9
Length of stay		
>14 days	1936	33.6
≤14 days	3822	66.4

*DS = data suppressed according to Healthcare Cost and Utilization Project/Nationwide Readmissions Database regulations.

DISCUSSION

Hydrocephalus is one of the most common clinical entities encountered by neurosurgeons, responsible for some 70,000 hospital admissions in the United States each year.[18] Because of the high rates of shunt-related complications, there is a

Table 5. Predictors of 90-Day All-Cause Readmissions by Multivariate Analysis Using Survey-Adjusted Logistic Regression

Variables	Odds Ratio	95% Confidence Interval		*P* Value
Gender				
Female	0.887	0.832	0.945	0.0002
Male	Reference			
Primary insurance				
Medicare	1.23	1.101	1.375	0.0003
Medicaid	1.066	0.953	1.192	0.2657
Self-pay	0.885	0.716	1.094	0.2594
No charge	1.313	0.736	2.342	0.3561
Other	0.857	0.705	1.042	0.1216
Private insurance	Reference			
Age				
18.1–44 years	1.156	0.999	1.337	0.0514
45–64 years	1.026	0.905	1.164	0.689
65–74 years	0.871	0.797	0.952	0.0024
≥75 years	Reference			
Elixhauser comorbidity				
Any one present	1.094	1.012	1.183	0.0245
None	Reference			
Diagnosis category				
Communicating hydrocephalus (331.3)	0.845	0.758	0.942	0.0023
Idiopathic normal pressure hydrocephalus (331.5)	0.692	0.629	0.761	<0.0001
Spina bifida–related hydrocephalus (741.xx)	0.792	0.52	1.206	0.2763
Congenital hydrocephalus (742.3)	0.686	0.494	0.954	0.0253
Multiple diagnoses	0.846	0.698	1.025	0.087
Obstructive hydrocephalus (331.4)	Reference			
Trauma				
Presence of traumatic brain injury	1.281	1.033	1.59	0.0244
None	Reference			
Hemorrhage				
Presence of subarachnoid hemorrhage intracerebral hemorrhage	0.916	0.827	1.016	0.0956
None	Reference			
Extracranial infection				
Yes	1.403	1.282	1.536	<0.0001
No	Reference			
Intracranial infection				
Yes	1.141	0.979	1.33	0.0914
No	Reference			
Tumor				
Yes	1.595	1.456	1.746	<0.0001
No	Reference			
Craniotomy				
Yes	1.104	1.002	1.217	0.0459
No	Reference			
Length of stay				
>14 days	1.087	0.99	1.194	0.0817
≤14 days	Reference			

substantial burden on health care resources tantamount to 400,000 hospital days and $100 million dollars annually.[23] Much of the literature on shunt failure was established in pediatric cohorts and the data in adults are notably sparse, limited to retrospective reviews from single institutions that often span decades. Although informative in highlighting the scope of the challenges in hydrocephalus management, these studies cannot be generalized to contemporary practices because they fail to account for evolving technologies and treatment patterns.

The NRD is the largest all-payer nationwide database in the United States designed for tracking patient readmissions, created to improve quality of health care and curb costs by penalizing institutions with excessive readmissions and, by proxy, substandard care. The NRD has been used in the neurosurgical literature to analyze readmission trends in subarachnoid hemorrhage,[24] stroke,[25] malignant brain tumors,[19] and cervical spine surgery.[26] However, this is the first study to evaluate readmission trends after hydrocephalus. We queried a large database with a heterogeneous population-based sample of 24,492 adults to determine shunt revision rates and identify predictors of readmission after shunt placement and estimate a shunt revision rate.

Previously reported 6-month shunt revision rates in adults range from 9% to 26%.[10,12,14,27] In our study, 9.17% of patients underwent a shunt revision within 6 months of initial placement. This figure is considerably lower than single-center reported rates for adults, likely because many existing studies are predicated on years of long-term follow-up versus the 6-month period specified in our analysis. Our value uniquely estimates shunt failure among a large population and within a clinically relevant time frame in which most failures are known to occur. Of shunts revised, 50%

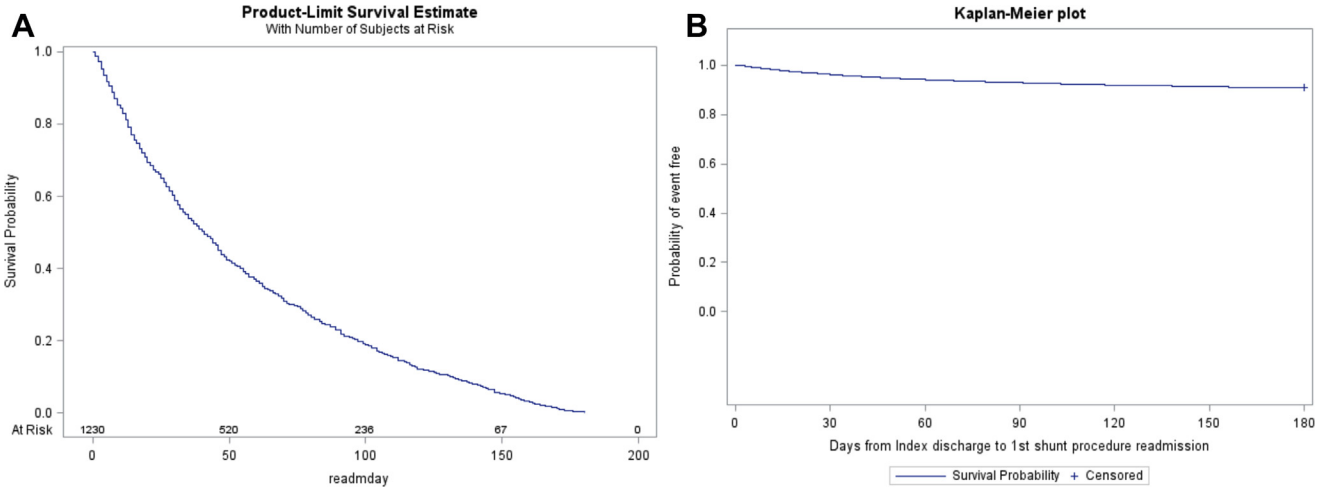

Figure 2. (**A**) Distribution of shunt failures within 6 months of placement. (**B**) Survival curve of ventricular shunts with 6 months of follow-up.

took place within 41 days of the index procedure, consistent with previous reports in the literature positing that even in adults, most failures happen in the immediate months after placement.[11,13,14,28]

Shunt failure arises from 3 major causes: infection, obstruction (proximal or distal), and overdrainage. Using the relevant *ICD-9* diagnosis codes, we were able to infer the various causes of shunt failure. Of patients revised at 6 months, 47.93% ($n = 590$) had a diagnosis of mechanical complication related to their shunt (*ICD-9* code 996.2), which likely corresponded to an obstruction of some kind; 22.75% ($n = 280$) had a diagnosis of shunt infection (*ICD-9* code 9966.3) and 14.38% ($n = 177$) had a diagnosis of overdrainage based on the *ICD-9* code 432.1. *ICD-9* code 432.1 has previously been used as surrogate for overdrainage.[11] The overall failure rates at 6 months among all patients shunted were thus determined to be 4.39% for obstruction, 2.08% for infection, and 1.32% for overdrainage. Few have performed similar analyses in a multistate database of adults with hydrocephalus. A study by Merkler et al.[11] reported a cumulative infection rate of 6.1% and an overdrainage rate of 14.1% over the course of 3.8 years of follow-up. Our rates are remarkably lower because of differences in the follow-up period specified. Moreover, our definition of shunt infection was restricted to a single *ICD-9* code (99663), which contrasts with the expansive list used by the study by Merkler et al. Their list includes several different meningitides and intracranial infections, which may or may not be immediately related to VP shunting. Accordingly, we chose to focus on the most clearly associated *ICD-9* code with VP shunt infection.

Within the index cohort, obstructive hydrocephalus (45.2%) accounted for most of the patients treated, followed closely by idiopathic NPH (38.2%) and communicating hydrocephalus (12.1%). The corresponding shunt revision rates were 11.31%, 7.21%, and 9.54%, respectively. Although our exploratory univariate analysis showed higher revision rates in obstructive causes and lower rates in NPH, after multivariable analysis we did not find a significant correlation between hydrocephalus classification and revision incidence. This finding contrasts with other reports in which NPH, for example, has had lower revision rates and longer time to shunt failure.[29] Patients with hemorrhage-related hydrocephalus did have lower odds for shunt revision within 6 months of placement (OR, 0.66; $P < 0.0001$). Similar findings have been reported in adult patients with hydrocephalus, including longer shunt survival.[10,30] However, this result has not been universally replicated: Reddy[13] found that hemorrhage-related hydrocephalus had a 51.9% shunt revision rate, and 45.1% of patients were revised within 6 months. Because the degree of blood and protein in CSF after ICH may change over time, it is possible that the timing of shunt surgery affects the rate of shunt survival. We found that patients with hemorrhage-related hydrocephalus also had a lower likelihood for readmission within 30 and 90 days. This situation may be caused by a more transient need for ventricular shunting in adults with posthemorrhagic hydrocephalus compared with other causes.

We discovered that patients who underwent ventriculopleural shunt placement were almost twice as likely to require revision within 6 months compared with patients with VP shunts (OR, 1.95; $P = 0.004$). A paucity of studies have reported this outcome. One series by Craven et al.[31] reported a mean 14-month shunt survival. There are several reasons why pleural shunts may be more likely to fail. Patients with pleural shunts may have underlying medical comorbidities that complicate shunt placement, such as peritonitis or a systemic disease with intra-abdominal manifestations. Pleural shunts may also be more poorly tolerated because they create pleural effusions that can lead to respiratory failure. It is possible that pleural shunts may be more likely to become infected or obstructed. Our report intimates that use of a pleural terminus should warrant higher vigilance for failure in the immediate perioperative period.

Age had an inverse correlation with odds of shunt revision. Those at greatest risk were patients aged 18–44 years, who had more than twice the risk of revision at 6 months compared with

Table 6. Demographics of Patients Shunted within 6 Months of Index Procedure

	Shunt		No Shunt	
Variables	**N**	**%**	**N**	**%**
Diagnosis				
Communicating hydrocephalus (331.3)	157	12.75	1488	12.2
Obstructive hydrocephalus (331.4)	617	50.12	5456	44.72
Idiopathic normal pressure hydrocephalus (331.5)	372	30.22	4784	39.22
Spina bifida—related hydrocephalus (741.xx)	15	1.22	51	0.42
Congenital hydrocephalus (742.3)	20	1.62	114	0.93
Multiple diagnoses	DS*		DS	
Total	1231	9.2	12199	90.8
Procedure				
Ventriculoatrial shunt (2.32)	24	1.95	170	1.39
Ventriculopleural shunt (2.33)	27	2.19	118	0.97
Ventriculoperitoneal shunt (2.34)	1178	95.69	11904	97.58
Multiple procedures	DS		DS	
Age				
18.1—44 years	292	23.72	1851	15.17
45—64 years	399	32.41	3448	28.26
65—74 years	259	21.04	3066	25.13
≥75 years	281	22.83	3834	31.43
Gender				
Male	645	52.4	6171	50.59
Female	586	47.6	6028	49.41
Primary insurance				
Medicare	612	49.72	7022	57.56
Medicaid	155	12.59	1307	10.71
Private insurance	395	32.09	3139	25.73
Self-pay	24	1.95	324	2.66
No charge	DS		34	0.28
Other	35	2.84	339	2.78
Hospital bed size				
Small	68	5.52	649	5.32
Medium	179	14.54	1884	15.44
Large	984	79.94	9666	79.24
Teaching status				
Metropolitan nonteaching	19	1.54	132	1.08
Metropolitan teaching	923	74.98	9312	76.33
Nonmetropolitan hospital	289	23.48	2755	22.58
Elixhauser comorbidity				
Any one present	886	71.97	9429	77.29
None	345	28.03	2770	22.71
Volume				
>90th percentile	516	41.92	5307	43.5
≤90th percentile (32/year)	715	58.08	6892	56.5
Trauma				
Presence of traumatic brain injury	28	2.27	238	1.95
None	1203	97.73	11961	98.05
Hemorrhage				
Presence of subarachnoid hemorrhage intracerebral hemorrhage	165	13.4	2066	16.94
None	1066	86.6	10133	83.06
Normal pressure hydrocephalus				
Yes	399	32.41	4972	40.76
No	832	67.59	7227	59.24
Extracranial infection				
Yes	211	17.14	1952	16
No	1020	82.86	10247	84
Intracranial infection				
Yes	63	5.12	489	4.01
No	1168	94.88	11710	95.99
Tumor				
Yes	258	20.96	2096	17.18
No	973	79.04	10103	82.82
Craniotomy				
Yes	203	16.49	1612	13.21
No	1028	83.51	10587	86.79
Length of stay				
>14 days	338	27.46	3477	28.5
≤14 days	893	72.54	8722	71.5

*DS = data suppressed according to Healthcare Cost and Utilization Project/Nationwide Readmissions Database regulations.

Continues

Table 7. Predictors of Shunt Revision within 6 Months of Index Placement as Determined by Multivariable Analysis Using Survey-Adjusted Logistic Regression

Variables	Odds Ratio	95% Confidence Interval		*P* Value
Primary insurance				
Medicare	1.124	0.933	1.355	0.2186
Medicaid	0.862	0.703	1.056	0.1507
Self-pay	0.564	0.369	0.864	0.0085
No charge	1.099	0.375	3.217	0.8632
Other	0.83	0.586	1.176	0.2945
Private insurance	Reference			
Age				
18.1–44 years	2.281	1.774	2.933	<0.0001
45–64 years	1.771	1.404	2.236	<0.0001
65–74 years	1.149	0.955	1.382	0.142
≥75 years	Reference			
Diagnosis category				
Communicating hydrocephalus (331.3)	0.983	0.816	1.185	0.8597
Idiopathic normal pressure hydrocephalus (331.5)	0.864	0.725	1.029	0.1019
Spina bifida–related hydrocephalus (741.xx)	1.716	0.952	3.095	0.0725
Congenital hydrocephalus (742.3)	1.109	0.675	1.822	0.6829
Obstructive hydrocephalus (331.4)	Reference			
Procedure category				
Ventriculoatrial shunt (2.32)	1.278	0.667	2.449	0.4597
Ventriculopleural shunt (2.33)	1.947	1.243	3.05	0.0036
Ventriculoperitoneal shunt (2.34)	Reference			
Hemorrhage				
Presence of any of subarachnoid hemorrhage intracerebral hemorrhage	0.661	0.548	0.797	<0.0001
None	Reference			
Craniotomy				
Yes	1.169	0.986	1.387	0.0721
No	Reference			

patients aged ≥75 years (OR, 2.28; $P < 0.0001$). This age-group was followed closely by patients 45–64 years, who had almost twice the odds of revision (OR, 1.77; $P < 0.001$). Although younger age has been previously linked to higher revision rates, this observation has generally been in the setting of distinguishing adults from pediatric cohorts. Other studies have not age-stratified an adult hydrocephalus population to show such a correlation. Univariate analysis confirmed lower likelihood for shunt failure among patients with NPH, but the correlation failed to meet significance in multivariate models. Younger age was also associated with increased likelihood for readmission within 30 and 90 days. These data suggest that closer surveillance might be warranted for young and middle-aged individuals who re shunted, more so than in the elderly.

Multivariate analysis was conducted to identify hospital-related and patient-related factors that influence readmission rates after shunt placement. In other conditions, hospital volume has been shown to have an inverse relationship with morbidity and mortality.[32,33] Work by Cochrane and Kestle[34] showed that such a relationship might also exist in hydrocephalus management, because they documented lower rates of infection and shunt failure with higher surgeon volume. We were unable to find a

Table 8. Most Frequently Coded Procedures During Readmission for Shunt Revision within 6 Months

Procedure (*International Classification of Diseases, Ninth Revision* Code)	Frequency	% Shunt Revisions
Replacement of ventricular shunt (2.42)	601	48.82
Removal of ventricular shunt (2.43)	353	28.68
Incision of peritoneum, catheter revision (54.95)	297	24.13
Irrigation and exploration of ventricular shunt (2.41)	185	15.03
Insertion or replacement of external ventricular drain (2.21)	129	10.48

statistically significant relationship between teaching status or hospital volume and rates of readmission or shunt complication. Another investigation using administrative claims data on shunt discharges from nonfederal emergency department and acute care hospitals in California, New York, and Florida also failed to unearth any association between procedure volume and shunt complications.[11]

Patients with Medicare insurance had increased odds of readmission within 30 and 90 days compared with individuals with private insurance. An analogous relationship was also established in recent work by our group characterizing readmission trends after craniotomy for malignant brain tumors.[19] This trend underscores the usefulness of analyzing all-payer databases to capture a heterogeneous study sample. Moreover, it points to possible inequities in health care rendered by hospitals based on insurance type. Similarly, Weygandt et al.[35] reported significant differences in mortality after blunt traumatic injury depending on insurance, with those on Medicare having higher odds of in-hospital death. Spencer et al.[36] in their analysis of discharge records from pooled state inpatient databases from 11 states between 2006 and 2008 reported that patients with private insurance tended to have lower risk-adjusted mortality than patients with Medicare when compared across 12 of 15 inpatient quality metrics. This association between insurance and 30-day and 90-day readmission deserves further examination and suggests that hospitals and policy makers might consider programs that monitor the quality of care delivered so as to minimize insurance-related disparities.

The presence of $\geq$1 comorbidities as determined by the Elixhauser Index correlated with increased likelihood for readmission within 30 and 90 days, as did a concomitant diagnosis of extracranial infection and tumor. Having undergone previous craniotomy and a history of traumatic brain injury were associated with 90-day readmission only. These observations are not surprising, because one might anticipate the presence of any of these circumstances warranting subsequent inpatient care, whether foreseeable or not. For example, those with tumors may require chemotherapy, radiation, and further oncologic management, and those with traumatic brain injury may require cranioplasty.

All reports using large administrative databases have important limitations. The NRD uses a state-linked identifier that is not triggered if readmission occurs in a different state from the index hospitalization. This strategy may underestimate readmission rates in clinical entities being studied. Concerns around patient confidentiality led to Healthcare Cost and Utilization Project excluding variables (e.g., race, state where admission occurred, and data that could identify a particular hospital) that prove informative from a demographic standpoint. Third, the NRD precludes tracking patients across calendar years. As a result, 30-day readmission numbers exclude data from December and 90-day readmission excludes data after September. Similarly, 6-month shunt revision rates do not report index admissions beyond June. Although this exclusion might skew reported numbers in a condition with seasonal variance, we do not believe that this is a major problem in hydrocephalus. Patients who die outside a hospital readmission in their home state are also lost to follow-up and are not included as readmissions or mortality in our analysis. Although we can address hospital volume, the NRD does not provide surgeon-level data for volume analysis. Without clinical information, we lack the ability to provide important contextual information associated with our patients' diagnoses and to further understand the causes of their hydrocephalus, reasons for ventricular shunt placement and subsequent revision. The NRD is not able to capture out-of-hospital deaths, and thus, we cannot report the mortality for patients using NRD data. If some disease states have substantial 6- month mortality, this could affect the accuracy of our estimates. Specific limitations that affect the fidelity of our analysis include our inability to determine whether the index placement was the first shunt insertion versus reinsertion after a period of externalization as is the case with infection. Additional concerns include those attributable to human error during database creation, such as inaccurate assignment of linkage numbers, data omission either from user error or incomplete hospital records, and miscoding.

CONCLUSIONS

In this study, we used the NRD to estimate the 6- month shunt revision rate and characterize predictors of both revision and 30-day and 90-day readmission after index shunt placement. The revision rate was determined to be 9.17% at 6 months, with half of revisions occurring within 2 months of initial placement. Younger age, Medicare insurance, ICH, and use of a ventriculopleural device were positive predictors of shunt revision. There was a significant association between hospital readmission and gender, insurance, length of hospitalization, age, existing comorbidities, and hydrocephalus cause. The link between insurance and risk of readmission after hydrocephalus is novel and deserves further investigation, because it suggests possible disparities in health care even among individuals treated within the same health care institutions.

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