Changes in treatment patterns of thoracoabdominal aortic aneurysms in the United States

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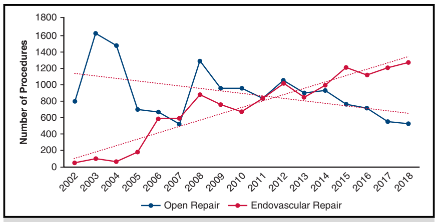
ABSTRACT

Background: The introduction of endovascular repair provides an alternative to traditional open repair of thoracoabdominal aortic aneurysms (TAAA). Its utility is not well defined, however. Using a national database, we studied the treatment patterns and outcomes of TAAA to gain insight into its contemporary surgical practice in the United States.

Methods: Records of TAAA patients who received endovascular and open repair were retrieved from the 2002 to 2018 National Inpatient Sample database. Each cohort was stratified into 4 age groups: ≤50, 51 to 60, 61 to 70, and >70 years. Patient characteristics and in-hospital outcomes were compared between the 2 repair modalities. Temporal trends were investigated.

Results: Endovascular repair use increased steadily, whereas open repair volume remained stable until 2012, before declining by 50% by 2018. This appears to be associated with a declining number of open repairs in patients age >60 years. Patients who underwent endovascular repair were older and had a higher Charlson Comorbidity Index (mean, 2.8 ± 1.7 vs 2.5 ± 1.5; *P* < .001) but lower in-hospital mortality (mean, 8.9% vs 17.1%; *P* < .001), shorter length of stay (mean, 10.1 ± 12.2 days vs 17.1 ± 17.4 days; *P* < .001), and fewer postoperative complications. A difference in mortality between open and endovascular repair was observed for patients age >60 years but not for patients age ≤60 years.

Conclusions: There has been a shift in the treatment of TAAA in the United States from open repair–dominant to endovascular repair–dominant. It has increased surgical access for older and more comorbid patients and has led to a decline in the use of open repair while lowering in-hospital mortality. (JTCVS Open 2023;16:48-65)



Trend in the number of procedures per year of open and endovascular TAAA repair, 2002 to 2018.

CENTRAL MESSAGE

Treatment of thoracoabdominal aneurysms appears to have shifted to endovascular repair over the last 2 decades, resulting in increased surgical access for older patients and decreased use of open repair.

PERSPECTIVE

Despite years of advances in the technique, open repair of thoracoabdominal aneurysm carries a high risk of complications. Endovascular repair may ameliorate this risk, but there is limited guidance on its use. Our findings show that endovascular repair may have replaced open repair as the predominant therapy and increases surgical access for older patients. This may optimize decision making when choosing between the repairs.

Thoracoabdominal aortic aneurysm (TAAA) is a rare and lethal aortic disease carrying a steep mortality rate when ruptured or dissected.[1-3] Similar to other aortic diseases, open repair has been the gold standard treatment for TAAA for decades.[1,4] Its outcomes appear to be highly variable, however, and operative mortality and morbidity remain persistently high.[5] In the last 20 years, the use of endovascular repair for the management of various aortic diseases has increased owing to the purported improvement in outcomes, length of stay, and short-term mortality.[4-6]

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Presented at the American College of Surgeons 108th Annual Clinical Congress, San Diego, California, October 2022.

Received for publication April 5, 2023; revisions received July 30, 2023; accepted for publication Aug 29, 2023; available ahead of print Oct 3, 2023.

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2666-2736

https://doi.org/10.1016/j.xjon.2023.08.019

Abbreviations and Acronyms

ICD-9-CM	= International Classification of Diseases, Ninth Revision, Clinical Modification
ICD-10-CM	= International Classification of Diseases, Tenth Revision, Clinical Modification
NIS	= National Inpatient Sample
TAAA	= Thoracoabdominal aortic aneurysm

However, the current state of this surgical practice in TAAA, and how it has changed since the introduction of endovascular repair, remain unclear.

The advent of endovascular repair has led to significant decreases in open repair for other aortic and vascular diseases that have been well studied; however, data specific to TAAA are limited. An earlier study describing national trends in TAAA repair between 1998 and 2007 reported increasing adoption of endovascular repair but stable use of open repair.[4] A similar trend was observed between 2005 and 2008 using a different database.[7] Little research on the subject has been published since then, and those studies likely do not reflect current surgical practice.

Despite years of advances in technique and perioperative care, open repair of TAAA continues to carry a high risk of complications. It is anticipated that endovascular repair may ameliorate some of these outcomes, but there is limited guidance on indications and patient selection.[8] A better understanding of the progression of TAAA surgery in recent decades may be beneficial in improving prognosis; thus, we sought to analyze data from a large national database over a 16-year study period to examine trends in use of the 2 surgical approaches, as well as the patient characteristics and treatment patterns that may be contributing to changes in practice.

METHODS

Data Source

The National Inpatient Sample (NIS) database, sponsored by the Agency for Healthcare Research and Quality, is part of the Healthcare Cost and Utilization Project (HCUP). The NIS is the largest publicly available all-payer administrative claims-based database containing patient discharge information from 4378 hospitals representing 20% of nonfederal hospitals in the United States. The NIS contains more than 100 clinical data elements from ~7 million unweighted hospitalizations annually. Using weights based on hospital-level discharges provided by the Healthcare Cost and Utilization Project, the NIS allows for estimation of ~35 million hospitalizations on a national level. Of note, the TRENDWT variable was used for weighting data prior to the 2012 NIS redesign and is consistent for analysis with the DISCWT variable after 2012. The NIS database reports data using the International Classification of Diseases, Ninth Revision, Clinical Modification (ICD-9-CM) until September 2015 and the International Classification of Diseases, Tenth Revision, Clinical Modification (ICD-10-CM) codes from October 2015 onward. Data from the NIS have been previously used to describe trends and outcomes for aortic interventions.[9,10] Comorbidities and complications can be identified using corresponding codes. Owing to the deidentified nature of the NIS database, Institutional Review Board approval and informed consent were not required for this study.

Study Population

We queried the NIS database using diagnosis codes from ICD-9-CM and ICD-10-CM and identified all records of hospitalizations for ruptured and unruptured TAAA between 2002 and 2018 (Table E1). Next, using procedure codes that specify the areas of the aorta undergoing operation, we generated subgroups in our patient cohort that underwent open repair or endovascular repair. Both subgroups were stratified into 4 age groups of patients age ≤50 years, 51 to 60 years, 61 to 70 years, and >70 years.

Patient and Hospital Characteristics

Baseline characteristics included patient demographics (eg, age, sex, race, primary payer information, and percentile of median household income) and their comorbidities.

Primary and Secondary Outcomes

Primary outcomes of interest were temporal trends of open repair versus endovascular repair in TAAA patients for procedure volume and as well as trends of in-hospital mortality. Secondary outcomes of interest included overall in-hospital mortality, length of stay, and complications in TAAA patients undergoing open or endovascular repair in both the overall cohort and the stratified age groups.

Statistical Analysis

Continuous variables were reported as mean with standard deviation (SD) and compared using the Student *t* test. Categorical variables were reported as number with percentage and compared using the Pearson chi-squared test. Longitudinal trends were analyzed using the Cochran-Armitage test for trends. Stata 16.0 (StataCorp) was used to complete all analyses in this study, applying sampling weights. All statistical tests were 2-tailed, and a P value < .05 was considered statistically significant.

RESULTS

National Trends in Surgical Volume and In-Hospital Mortality

A weighted total of 125,151 patients diagnosed with TAAA between 2002 and 2018 were identified. Of these, 15,228 patients underwent open repair and 12,341 underwent endovascular repair. The annual incidences of TAAA, plotted in Figure E1, show a steady decrease in diagnoses since 2008. The numbers of open and endovascular procedures performed annually between 2002 and 2018 are presented in Figure 1 for the total surgical cohort. Endovascular repair use consistently increased from 48 operations in 2002 to 1270 operations in 2018. The use of open repair was largely stable between 2002 and 2011, averaging approximately 980 cases per year. Between 2012 and 2018, open repair decreased by 50%. The slopes of the 2 trends intersect between 2011 and 2012. The P trend in Figure 1 was $P < .001$, indicating an increase in endovascular repair compared to open repair. Hybrid repairs including both modalities in a single admission are shown in Figure E2, with a peak of 60 cases per year. Surgical volume for both repairs further stratified by regions in the US showed similar trends to those seen at the national level (Figure E3). In-hospital mortality spanning the same time frame is graphed for each repair in Figure 2. A downward trend in mortality for both repair modalities was observed, with a P trend of $P < .001$ for open repair and $P = .002$ for endovascular repair.

Patient Characteristics

Patient characteristics and comorbidities are summarized in Table 1. Open repair patients were younger than endovascular patients (67.1 years vs 72.1 years; $P < .001$). Although most patients in both groups were age >60, patients age >70 were predominant in the endovascular group (62.1%).

Open repair patients had lower incidences of comorbidities, including diabetes (9.5% vs 13.1%; $P < .001$), hypertension (53.1% vs 60.8%; $P < .001$), dyslipidemia (28.0% vs 43.6%; $P < .001$), coronary artery disease (39.8% vs 44.5%; $P < .005$), and chronic kidney disease (15.9% vs 23.7%; $P < .001$). Compared to endovascular patients, they had a lower Charlson Comorbidity Index (2.5 vs 2.8; $P < .001$), were less likely to be smokers (36.6% vs 52.4%; $P < .001$), and more likely to have Marfan syndrome (2.5% vs 0.6%; $P < .001$). Among the total cohort, 11.9% presented with ruptured aneurysms (13.7% of open repair patients and 9.6% of endovascular repair patients), and 88.1% had unruptured aneurysms.

In-Hospital Outcomes of Open versus Endovascular Repair

Outcomes of the surgical cohort are reported in Table 2. Open repair patients had higher in-hospital mortality (17.1% vs 8.9%; $P < .001$), longer length of stay (mean, 17.1 ± 17.4 days vs 10.1 ± 12.2 days; $P < .001$), and increased rates of postoperative complications in all studied categories: cardiac (18.3% vs 8.4%; $P < .001$), respiratory (45.4% vs 21.2%; $P < .001$), renal (37.1% vs 21.6%; $P < .001$), stroke (4.5% vs 3.4%; $P = .001$), paralysis (5.0% vs 3.8%; $P = .008$), and spinal cord injury (3.3% vs 2.3%; $P = .007$). From 2002 to 2018, in-hospital mortality for both repair modalities decreased steadily at similar rates (Figure 2).

In-Hospital Outcomes Stratified by Age

Both open and endovascular patients were stratified into 4 age groups of patients and in-hospital mortality and length of stay were compared (Table 3). There was no significant difference in in-hospital mortality or length of stay between the open and endovascular groups in patients age ≤50 years. In patients age 51 to 60 years, there was no difference in in-hospital mortality between the groups, but length of stay was longer in open repair patients (16.5 days vs 9.1 days; $P < .001$). In patients age 61 to 70 years, the open repair group had greater in-hospital mortality (16.0% vs 7.8%; $P < .001$) and longer length of stay (17.0 days vs 9.8 days; $P < .001$). This was also observed in patients age >70 years (in-hospital mortality: 22.6% vs 9.8% [$P < .001$]); length of stay (17.4 days vs 10.2 days, $P < .001$) (Table 3).

National Trends in Procedure Volume and In-Hospital Mortality Stratified by Age

The data shown in Figures 1 and 2 were further stratified into age groups and are graphed in Figures 3, 4, and E1. Both repairs had an up-trending procedure volume in patients age ≤50 years (Figure 3, *A*). The same trend was seen in patients age 51 to 60 years, with endovascular repair displaying a steeper uptrend (Figure 3, *B*). In the oldest age groups, the use of open repair declined, whereas endovascular repair increased. The 2 curves intersected in 2013 in the 61 to 70 age group (Figure 3, *C*) and in 2009 in the >70 age group (Figure 3, *D*). An aggregate of these trendlines is represented in Figure E4. In patients age 61 to 70 years, a downward mortality trend was seen in endovascular repair and a stable trend was seen in open repair (Figure 4, *A*); however, in-hospital mortality was most evident over time

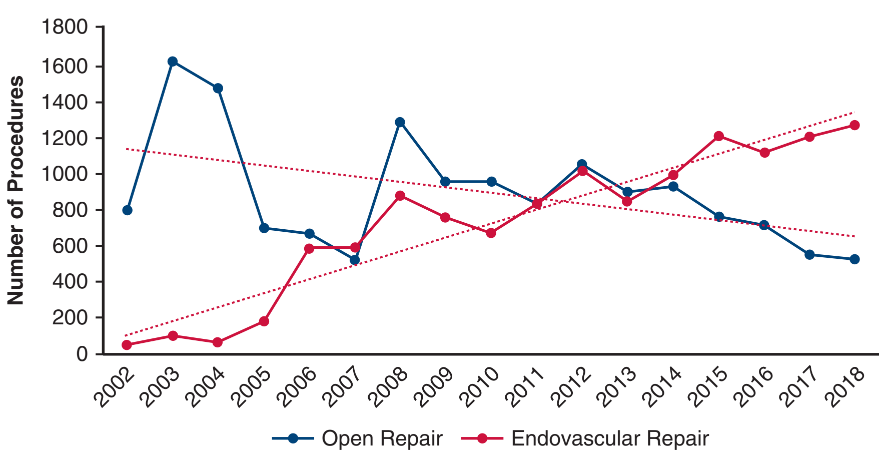

FIGURE 1. National trends in the number of procedures completed per year for open and endovascular TAAA surgical repair, 2002 to 2018.

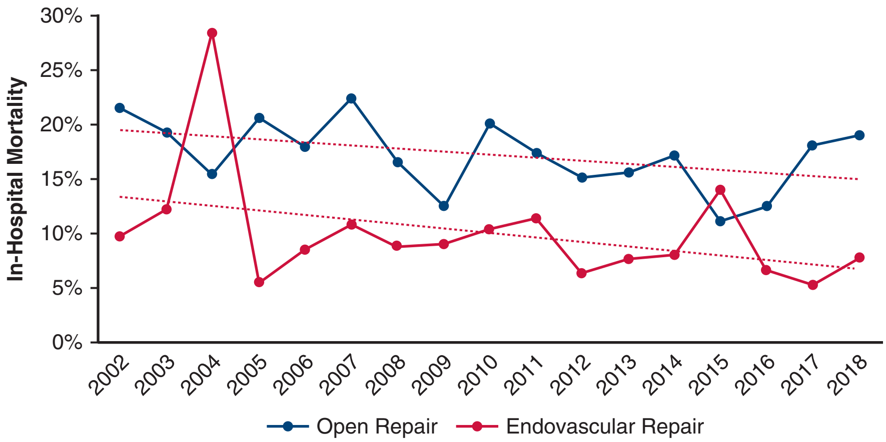

FIGURE 2. National trends in in-hospital mortality per year for open and endovascular TAAA surgical repair from 2002 to 2018. Both curves exhibit a downward trend.

in patients age >70 years, in whom downward trends were seen in both repair modalities (Figure 4, *B*). In the other age groups, stable mortality trends were observed for both repairs (Figure E5).

DISCUSSION

Here we describe the apparent replacement of open repair by endovascular repair as the predominant surgical modality in TAAA patients, with declining use of open repair over the last decade. Patients age 60 years contributed the most to this reversal. The outcomes of endovascular patients appeared to be superior to those of open repair patients, which was especially evident in older patients despite their greater comorbidity burden.

The decline of open repair in favor of endovascular repair is well described in other aortic and vascular diseases, such as abdominal aortic aneurysm (AAA) and thoracic aortic aneurysm (TAA). Improved outcomes and management associated with endovascular repair have driven this shift.[4,7,11] In AAA, endovascular aortic repair comprises 80% of repair procedures.[12] In TAAA, thoracic endovascular aortic repair can be associated with better outcomes over open aortic repair despite concerns about long-term outcomes and reinterventions.[13,14] However, specific data on TAAA is lacking in the literature. Databases such as the Vascular Quality Initiative and National Surgical Quality Improvement Program contain data with similar baseline patient characteristics and in-hospital outcomes as NIS, although with a notably smaller sample size.[15,16] Scali and colleagues[4] and Liao and colleagues[7] examined TAAA surgical practice in the early 2000s and observed a rapid increase in use of endovascular repair while the use of open repair remained stable. The growth in endovascular repair observed here continued throughout the study period, driven primarily by patients age >70 years, the largest cohort in our study for both repair modalities. Previous reports indicated that patients in their 60s represented the majority of TAAA surgical repairs.[17,18] This transition highlights an aging cohort that is increasingly being offered surgical interventions because of improved technique and growth of endovascular repair.[19,20] To our knowledge, this is the first time that TAAA surgical repair has been observed to align with contemporary trends in the management of other aortic diseases.

Our data reveal superior in-hospital mortality, length of stay, and postoperative complications with endovascular repair compared to open repair. A previous study examining data during the nascency of endovascular repair in the early 2000s found that despite the rapid adoption of endovascular repair, mortality and morbidity in TAAA repairs remained high even at experienced centers.[4] This finding contrasts with studies reporting that outcomes of open TAAA repair can be excellent in experienced hands.[1,21-23] Other reports suggest that there is room for improvement in overall open repair outcomes.[2,5,24] Given this wide variation in conclusions and the absence of a TAAA-specific database, our query of the NIS database has uncovered possible reasons describing the current state of practice, as well outcomes data that otherwise might not be available. Although we were unable to differentiate between high-volume and low-volume centers, the contrast in outcomes was notable. Our findings align with contemporary reports, demonstrating that endovascular repair offers better in-hospital results and fewer complications than open repair, expanding surgical options for patients who might not be suitable for open repair.

Among patients age >60, we observed significant improvements in in-hospital mortality with endovascular repair compared with open repair. Meanwhile, in younger patients, particularly those age ≤50, open repair yields excellent outcomes comparable to those of endovascular repair. This trend gradually diminishes with age. How age

TABLE 1. Baseline patient characteristics and comorbidities of TAAA patients

Characteristic/outcome	Open repair (N = 15,228)	Endovascular repair (N = 12,341)	*P* value
Patient characteristics			
Age, y, mean ± SD	67.1 ± 11.4	72.1 ± 10.0	<.001
Age, y, n (%)			<.001
≤50	1380 (9.1)	421 (3.4)	
51-60	1921 (12.6)	857 (6.9)	
61-70	5173 (34.0)	3401 (27.6)	
>70	6755 (44.4)	7663 (62.1)	
Female sex, n (%)	6670 (43.8)	5139 (41.6)	.08
Race, n (%)			.73
White	9944 (76.7)	8125 (76.3)	
Black	1605 (12.4)	1364 (12.8)	
Hispanic	604 (4.7)	423 (4.0)	
Asian/Pacific Islander	236 (1.8)	260 (2.4)	
Native American	63 (0.5)	54 (5.1)	
Other	515 (4.0)	422 (4.0)	
Primary expected payer, n (%)			<.001
Medicare	9844 (64.7)	9516 (77.3)	
Medicaid	949 (6.2)	455 (3.7)	
Private insurance	3714 (24.4)	1818 (14.8)	
Self-pay	327 (2.2)	136 (1.1)	
Percentile of median household income, n (%)			.82
<25	2873 (26.6)	3092 (26.3)	
25-49	2847 (27.1)	3238 (27.6)	
50-74	2615 (25.6)	2910 (24.9)	
≥75	2105 (20.7)	2461 (21.2)	
Comorbidities			
Charlson Comorbidity Index, mean ± SD	2.5 ± 1.5	2.8 ± 1.7	<.001
Marfan syndrome, n (%)	385 (2.5)	73 (0.6)	<.001
Primary hypertension, n (%)	8090 (53.1)	7509 (60.8)	<.001
Coronary artery disease, n (%)	6059 (39.8)	5494 (44.5)	.004
Congestive heart failure, n (%)	2129 (14.0)	1965 (15.9)	.08
Diabetes mellitus, n (%)	1443 (9.5)	1617 (13.1)	<.001
Dyslipidemia, n (%)	4258 (28.0)	5380 (43.6)	<.001
Chronic obstructive pulmonary disease, n (%)	5772 (37.9)	4976 (40.3)	.08
Stroke/transient ischemic attack, n (%)	1986 (13.0)	1663 (13.5)	.84
Chronic kidney disease, n (%)	2422 (15.9)	2919 (23.7)	<.001
Chronic liver disease	176 (1.2)	110 (0.9)	.23
Cirrhosis, n (%)	39 (0.3)	34 (0.3)	.94
Human immunodeficiency virus, n (%)	92 (0.6)	64 (0.5)	.61
Smoking, n (%)	5580 (36.6)	6460 (52.4)	<.001

TAAA, Thoracoabdominal aortic aneurysm.

influences decision making in TAAA management is undefined. Large single-center studies have described excellent outcomes of open repair in patients age ≤50 years, consistent with our findings.[18,25-27] Conversely, octogenarians can be associated with in-hospital mortality exceeding 20%.[17,28] Data specific to patients age 51 to 70 years are scarce in the literature. Our data describing comparable survival between open repair and endovascular repair for patients in their 50s but not in their 60s may provide important insight, considering that a significant portion of patients undergoing TAAA repair are found in this age range. This survival benefit also may be an important driver of the uptrending volume of endovascular repair.

Between 2002 and 2018, both open repair and endovascular repair showed a slight decline in in-hospital mortality, reflecting expected improvements in surgical techniques and medical therapy. Experts have reported numerous factors contributing to improved mortality in TAAA repair, including high-volume centers, surgeon expertise, and hospital size.[13,29,30] However, the literature lacks specific explanations regarding the patient characteristics associated with this declining mortality. We anticipated a decrease in

TABLE 2. In-hospital complications and outcomes in TAAA patients

Complication/outcome	Open repair (N = 15,228)	Endovascular repair (N = 12,341)	*P* value
Complications			
Cardiac, n (%)	2785 (18.3)	1034 (8.4)	<.001
Respiratory, n (%)	6911 (45.4)	2614 (21.2)	<.001
Renal, n (%)	5651 (37.1)	2671 (21.6)	<.001
Stroke, n (%)	683 (4.5)	423 (3.4)	.001
Paralysis, n (%)	762 (5.0)	463 (3.8)	.008
Spinal cord injury, n (%)	507 (3.3)	288 (2.3)	.007
Outcomes			
Mortality, n (%)	2595 (17.1)	1091 (8.9)	<.001
Length of stay, d, mean ± SD	17.1 ± 17.4	10.1 ± 12.2	<.001

TAAA, Thoracoabdominal aortic aneurysm.

open repair mortality in our data, particularly with older patients who once would have received open repair transitioning to endovascular repair instead. We observed this for both repairs in patients age >70 but only in endovascular repair in patients age 61 to 70. The reduced mortality in patients age >70 was the primary contributor to the improved mortality. Interestingly, despite the increase in endovascular repair volume and the corresponding decrease in open repairs over the past decade, the shift in practice has not translated into an in-hospital survival benefit for patients age 61 to 70 who undergo open repair. This suggests that future efforts at refining patient selection are warranted to improve outcomes.

The trends observed in this study also can be attributed to several factors that are not captured by the data. Important among these are the evolution of devices and techniques, use of enhanced imaging capabilities, and establishment of dedicated multidisciplinary aortic teams.[31,32] Although the NIS cannot capture details on these topics, they are central factors to understanding the landscape of TAAA repair over the last 2 decades and likely influenced the observed trends.

During the infancy of TAAA endovascular repair, the lack of readily available manufactured fenestrated devices tailored to patients' anatomy led to the adoption of physician-modified endovascular grafts (PMEGs). These grafts involved the creation of fenestrations within existing Food and Drug Administration-approved stents to conform them to the unique requirements of each TAAA case.[33,34] PMEGs effectively reduced spinal cord injury, renal ischemia, and other distal perfusion complications[34,35]; however, patients were at high risk of endoleaks and required frequent reintervention. Quality control also posed a challenge.[36]

In the last 2 decades, durable, specialized fenestrated-branched "off-the-shelf" devices and custom-made devices have largely replaced PMEGs.[35] These include low-profile devices and preloaded wire systems that allow for more efficient repair.[32] This has led to decreased endoleaks, increased availability for more patients, and reduced complications comparable to those of open repair.[37] Despite this, Food and Drug Administration approval for a TAAA-specific device was granted only recently, with commercial production still pending (Cook Medical), whereas

TABLE 3. In-hospital outcomes of TAAA patients stratified by age

Outcome	Open repair (N = 15,228)	Endovascular repair (N = 12,341)	*P* value
Age ≤50 y			
Mortality, %	5.1	5.8	.73
Length of stay, d, mean ± SD	16.2 ± 20.5	12.0 ± 17.4	.13
Age 51-60 y			
Mortality, %	9.4	6.0	.19
Length of stay, d, mean ± SD	16.5 ± 15.5	9.1 ± 9.0	<.001
Age 61-70 y			
Mortality, %	16.0	7.8	<.001
Length of stay, d, mean ± SD	17.0 ± 17.2	9.8 ± 11.9	<.001
Age >70 y			
Mortality,%	22.6	9.8	<.001
Length of stay, d, mean ± SD	17.4 ± 17.4	10.2 ± 12.3	<.001

TAAA, Thoracoabdominal aortic aneurysm.

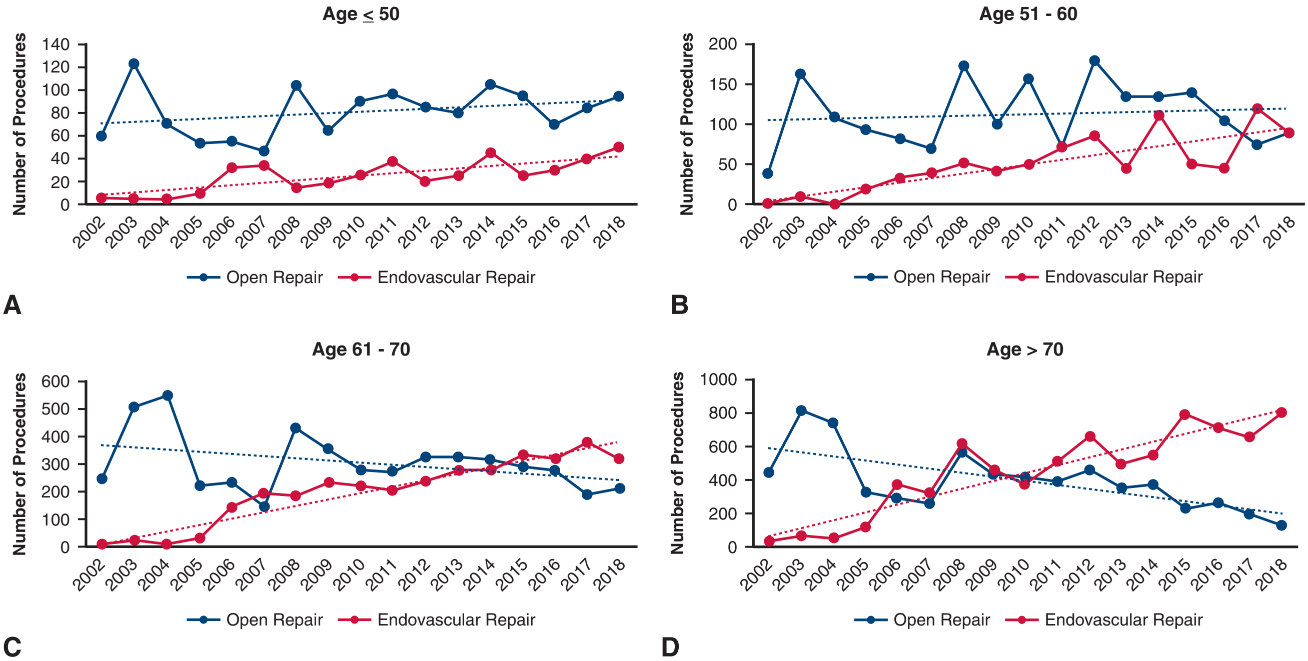

FIGURE 3. National trends in the number of procedures completed per year for open and endovascular TAAA surgical repair from 2002 to 2018 by age group. (A) ≤50 years. (B) 51 to 60 years. (C) 61 to 70 years. (D) >70 years.

multiple devices for AAA and TAA have been approved and manufactured.

These advancements in devices produce an inherent increase in learning curve difficulty for surgeons as they adapted to new technology and methods.[38,39] Despite this, the use of endovascular repair has risen dramatically in a timeline consistent with our data on increasing procedure volume over the study period.

Concurrent improvements in preoperative planning and preparation, facilitated by advanced imaging and establishment of multidisciplinary aortic teams, have further contributed to these trends. The proliferation of hybrid operating rooms with fixed imaging capabilities, such as fluoroscopy and cone beam computed tomography, is apparent nationwide. This has provided notable improvements in patient selection, planning, and endovascular repairs compared with portable C-arm scanners used in the early 2000s.[32,39] Many of these hybrid operating rooms are located in centers with aortic teams composed of specialists from multiple disciplines such as cardiovascular surgery, vascular surgery, interventional radiology, cardiology, anesthesiology, and critical care. These teams have robust experience and collaborate on aortic patient management, resulting in reduced mortality and complications for both repairs.[5,30] Referrals within the team led to appropriate selection of the type of repair and likely played a part in the increase in endovascular repair observed in this study. They are also valuable in the treatment of complex type II and III TAAAs, where the aneurysm spans both the thoracic and abdominal cavities, posing additional risk for complications

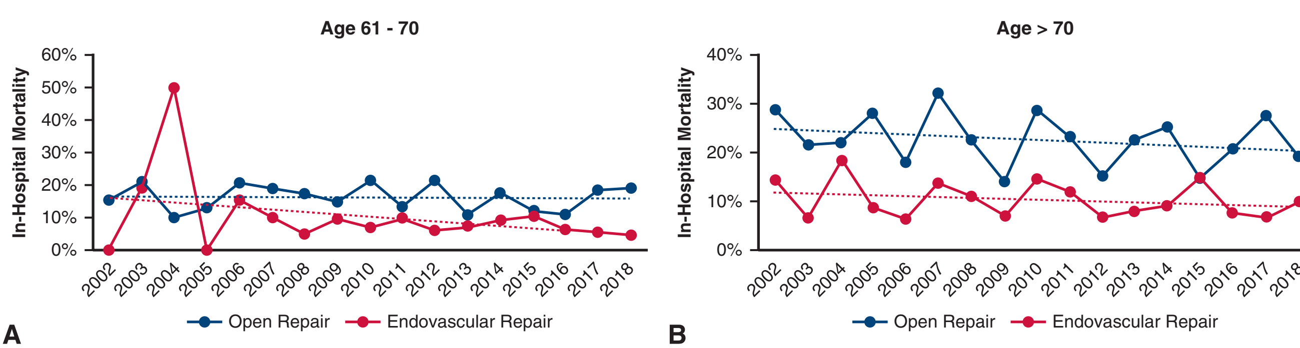

FIGURE 4. National trends in in-hospital mortality per year for open and endovascular TAAA surgical repair from 2002 to 2018 in the 61 to 70 year (A) and >70 year (B) age groups. Both open repair curves exhibit downward trends.

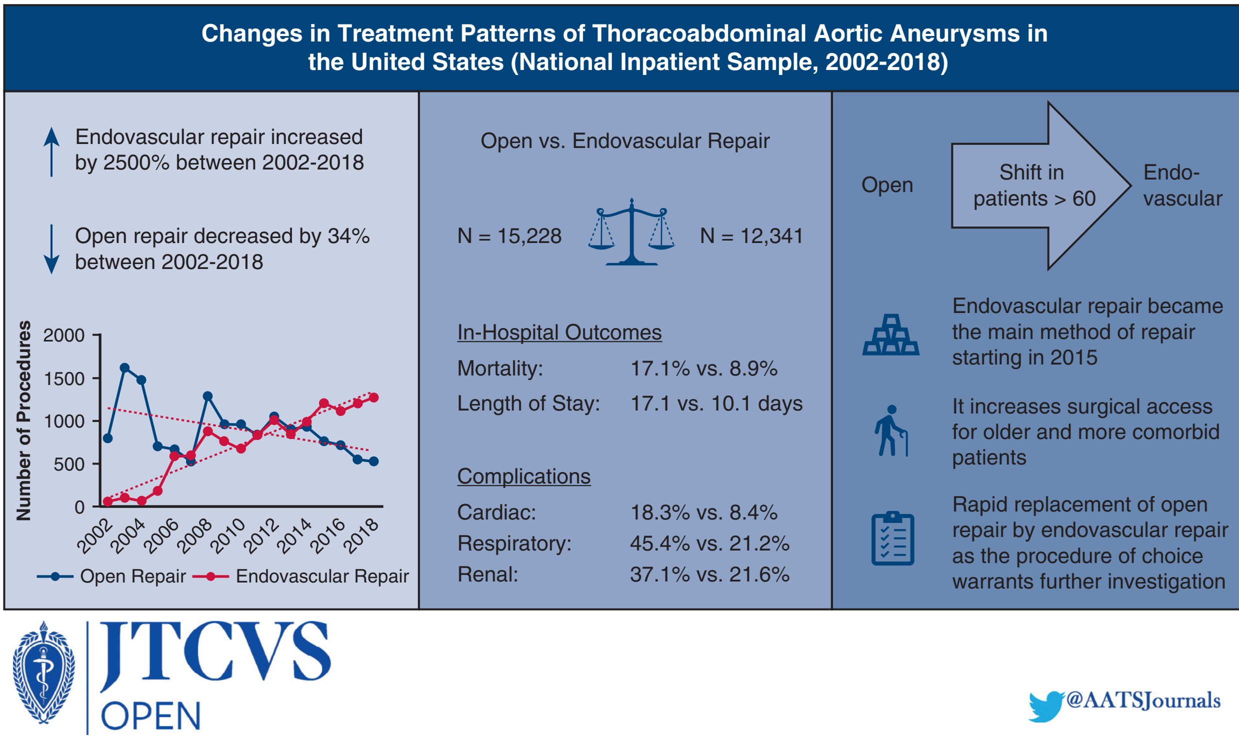

FIGURE 5. Graphical abstract depicting the main study objectives and results.

and challenges and increasing the likelihood of open repair.[31,37]

These elements may provide insight into the observed decline in open repair. Although there have been advances in both techniques over the past 2 decades, it is reasonable to conclude that the strides in endovascular repair have eclipsed and outpaced those in open repair. Endovascular repair boasts improvements in technology, technique, and planning, whereas open repair improvements have been mainly in technique. Specifically, these improvements include maximizing distal perfusion by moving away from early methods such as "clamp and go" and using such techniques as cerebrospinal fluid drainage and deep hypothermia.[38-40]

Here we describe the current state of surgical repair in TAAA patients and its evolution over the last 2 decades (Figure 5). Although delayed, it appears that TAAA has progressed to a point in therapy that aligns with other aortic and vascular diseases in which the volume of endovascular repair has increased while that of open repair has decreased. Potential explanations for this trend are provided by the data through greater numbers of procedures in older patients, improved in-hospital outcomes and complications of endovascular repair, and steadily improved mortality. Other factors include the use of more effective endovascular technology and higher-resolution imaging, formation of multidisciplinary aortic teams, and outpacing of advances in open repair. Future studies should include data from other, more granular databases, such as the Society for Thoracic Surgeons Adult Cardiac Surgery Database and the Vascular Quality Initiative registry. These databases may provide further information concerning therapy for nonsurgical patients, high- and low-volume centers, technology, complications, and identification of anatomy. NIS data for the years after 2018 also would be useful in confirming the continuation of the current trajectory of TAAA repair. Finally, the development of a TAAA-focused national or international database can support continued advancement of TAAA management guidelines and bring them more in line with other well-studied aortic and vascular diseases.

Limitations of this study arise primarily from use of the NIS database. First, the NIS does not allow for longitudinal analysis of patient records. Long-term mortality and morbidity or reinterventions cannot be differentiated. These are important areas of research for endovascular repair and provide more comprehensive descriptions of the utility of each repair modality. Additionally, the NIS was unable to identify the technology used and level of center expertise. Despite this, we have provided new data on open repair versus endovascular repair in TAAA that serves as a path to further research.

Second, NIS provides limitations in the use of ICD codes. Our study period includes the third quarter 2015 transition from ICD-9-CM to ICD-10-CM, which introduced variability into the dataset. Neither ICD code set contains descriptions of such anatomic features as aneurysm size and Crawford classification, important surgical features whose management has evolved concurrently with the trends seen in this study. Specific patient anatomic features were not of critical importance to the conclusions drawn, however. Regarding postoperative complications, although many of the codes can specify whether a condition was present on admission versus acquired postoperatively, several do not contain time-specific qualifiers. Nevertheless, our rates of complications align with those reported in contemporary studies and highlight the greater risk of complications associated with open repair.[41] Overall, the codes used in this study were carefully selected based on multiple NIS publications studying similar topics, and the data were vetted for errors.

Finally, there is an inherit selection bias present in national databases in which individual patients are chosen for one approach over the other. As such, this bias is difficult to overcome in this type of study.

CONCLUSIONS

The surgical treatment of TAAA appears to have shifted from open repair–dominant to endovascular repair–dominant. This change, seen primarily in patients age >60, has increased patients' access to surgical treatment and is associated with lower in-hospital mortality. Mortality of both open repair and endovascular repair has declined over the past 2 decades. The rapid replacement of open repair by endovascular repair as the procedure of choice warrants further investigation.

Conflict of Interest Statement

The authors reported no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling or reviewing manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

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Key Words: thoracoabdominal aortic aneurysm, open repair, endovascular, in-hospital mortality, surgical trends

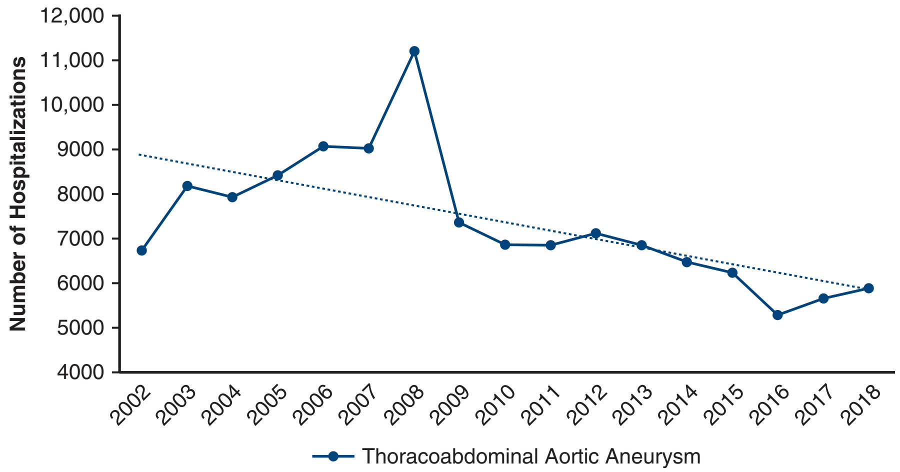

FIGURE E1. Annual incidence of thoracoabdominal aortic aneurysm from 2002 to 2018. The incidence appears to have peaked in 2008 and decreased steadily thereafter.

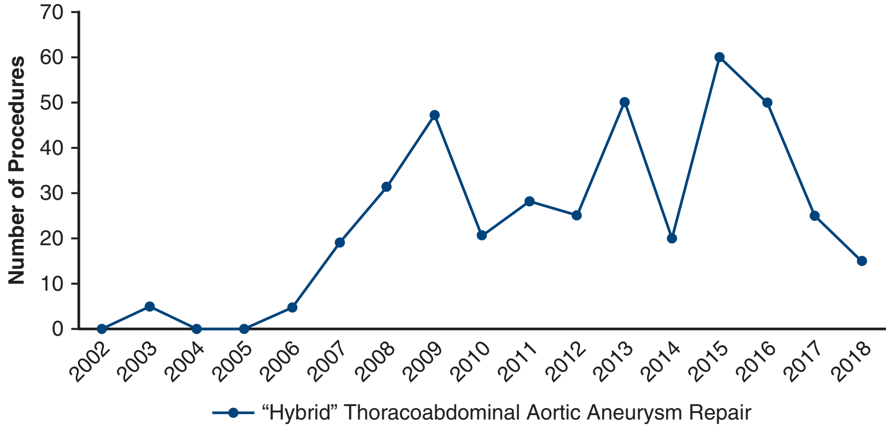

FIGURE E2. Number of thoracoabdominal aortic aneurysm patients receiving hybrid surgical repair (ie, both open and endovascular repair in the same hospital admission). The trend has been variable, but cases do not exceed 60 per year. Mean age is 68.3 ± 11.3 years, and in-hospital mortality is 20.7%.

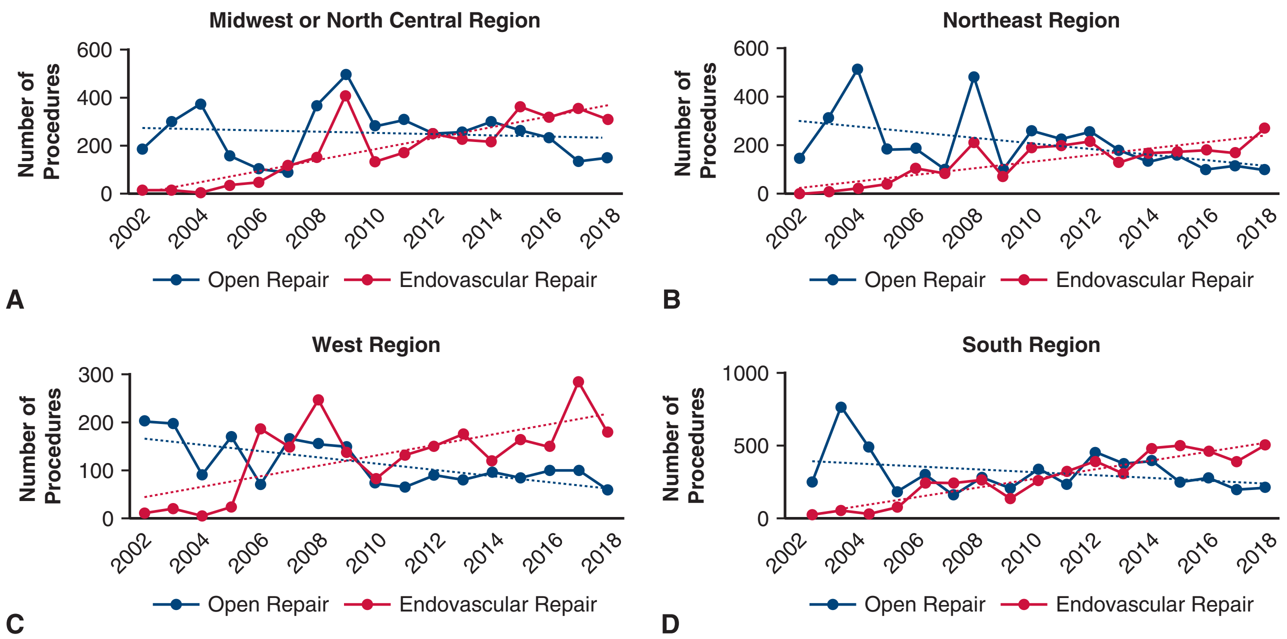

FIGURE E3. Regional trends of open repair and endovascular repair of thoracoabdominal aortic aneurysm for the Midwest (A), Northeast (B), West (C), and South (D) regions. Trends for both repair modalities are consistent with trends seen at the national level.

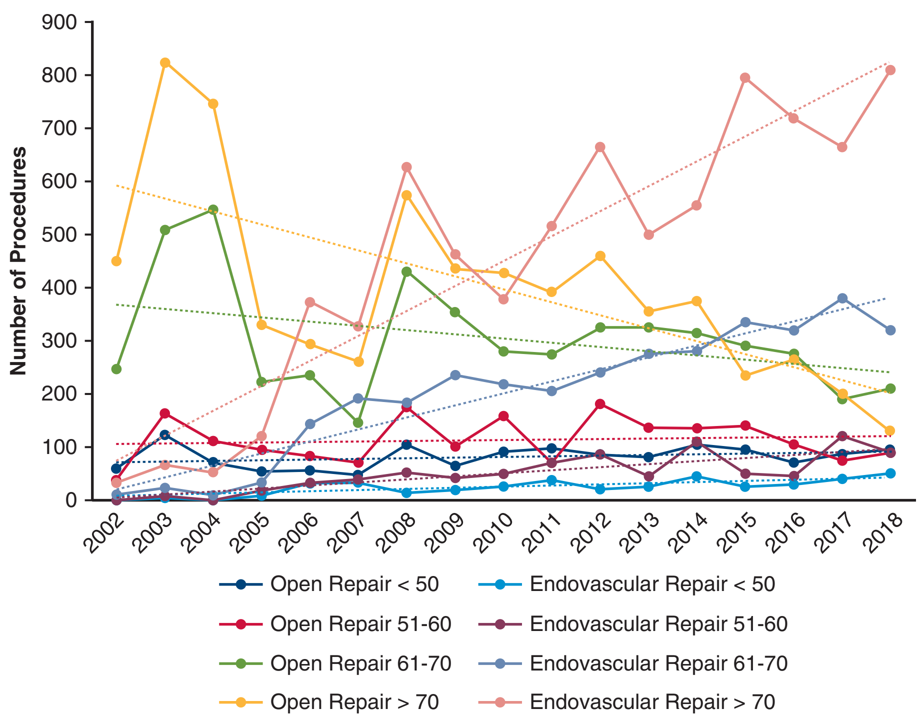

FIGURE E4. Aggregate trend lines for open repair and endovascular repair of thoracoabdominal aortic aneurysm in patients age ≤50 years, 51 to 60 years, 61 to 70 years, and >70 years.

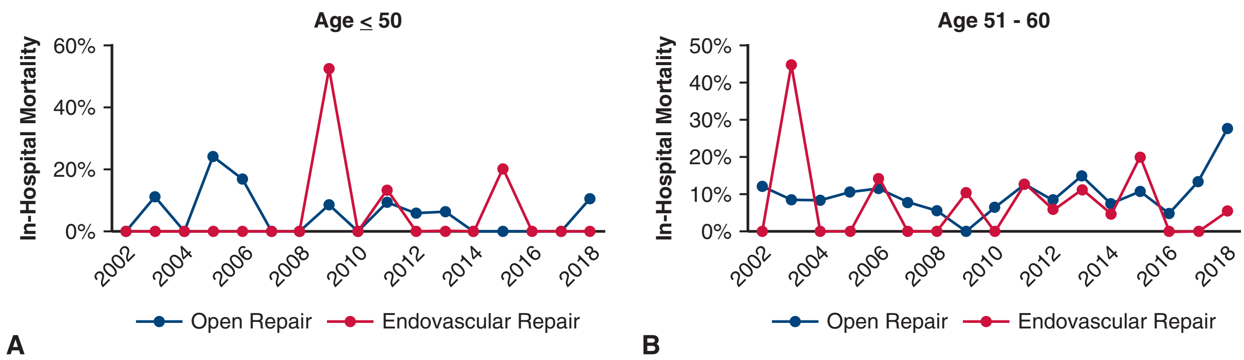

FIGURE E5. National trend of in-hospital mortality percentages per year for open repair and endovascular repair of thoracoabdominal aortic aneurysm from 2002 to 2018 in patients age ≤50 years (A) and age 51 to 60 years (B).

TABLE E1. ICD-9-CM and ICD-10-CM Diagnosis and Procedure Codes

Diagnosis/procedure	ICD-9-CM diagnosis codes	ICD-9-CM procedure codes	ICD-10-CM diagnosis codes	ICD-10-CM procedure codes
Thoracoabdominal aortic aneurysm	441.6		I71.5	
	441.7		I71.6	
Open repair		38.34		04Q00ZZ
		38.35		02QW0ZZ
		38.44		04R00JZ
		38.45		02RW0JZ
				04U00JZ
				02UW0JZ
				04V00ZZ
				02VW0ZZ
				04B00ZZ
				02BW0ZZ
Endovascular repair		39.73		02VW3*
		39.71		02VW4*
		39.78		04V03*
				04V04*
Marfan syndrome	759.82		Q87.40	
			Q87.410	
			Q87.418	
			Q87.42	
			Q87.43	
Ehlers–Danlos syndrome	756.83		Q79.60	
			Q79.61	
			Q79.62	
			Q79.63	
			Q79.69	
Loeys–Dietz syndrome	759.89		Q87.89	
Primary hypertension	401*		I10	
	402*		I110	
			I119	
Coronary artery disease	440		I70.0	
	440.1		I70.1	
			I25.10	
			I25.8	
Congestive heart failure	398.91		I09.9	
	402.01		I11.0	
	402.11		I13.0	
	402.91		I13.2	
	404.01		I25.5	
	404.03		I42.0	
	404.011		I42.5-I42.9	
	404.13		I43.*	
	404.91		I50.*	
	404.93		P29.0	

(Continued)

TABLE E1. Continued

Diagnosis/procedure	ICD-9-CM diagnosis codes	ICD-9-CM procedure codes	ICD-10-CM diagnosis codes	ICD-10-CM procedure codes
	425.4-425.9			
	428.*			
Diabetes mellitus	250.0-250.3		E10.10	
	250.8		E10.2-E10.5	
	250.9		E10.6	
			E10.8	
			E10.9	
			E11.0	
			E11.1	
			E11.2-E11.5	
			E11.6	
			E11.8	
			E11.9	
			E13.0	
			E13.1	
			E13.2-E13.5	
			E13.6	
			E13.8	
			E13.9	
Dyslipidemia	272.4		E78.4	
			E78.5	
Chronic obstructive pulmonary disease	416.8		I27.8	
	416.9		I27.9	
	490.*-505.*		J40.*-J47.*	
	506.4		J60.*-J67.*	
	508.1		J68.4	
	508.8		J70.1	
			J70.3	
Stroke/transient ischemic attack	430.*-436.*		G45.*	
	438.*		G46.*	
	V17.1		I60.*	
			I61.*	
			I62.*	
			I63.*	
			I69.*	
Chronic kidney disease	403.01		I12.0	
	403.11		I13.1	
	403.91		N03.2-N03.7	
	404.02		N05.2-N05.7	
	404.03		N18.*	
	404.12		N19.*	
	404.13		N25.0	
	404.92		Z49.0-Z49.2	
	404.93		Z94.0	

(Continued)

TABLE E1. Continued

Diagnosis/procedure	ICD-9-CM diagnosis codes	ICD-9-CM procedure codes	ICD-10-CM diagnosis codes	ICD-10-CM procedure codes
	582.*		Z99.2	
	583.0-586.7			
	588			
	V42.0			
	V45.1			
	V56.*			
Chronic liver disease	070.2-070.6		K70.0	
	070.9		K70.2	
	571.0		K73*	
	571.3		K75.4	
	571.4		K75.8	
	571.8		K75.9	
	573.1		K76.0	
	573.3		B18.0-B18.2	
			B18.8	
			B18.9	
Cirrhosis	456.1		I85.9	
	571.2		I98.2	
	571.5		K70.3	
			K71.7	
			K74.6	
Human immunodeficiency virus	070.51		B17.1	
	070.54		B18.2	
	V02.62		Z22.52	
	292.0		Z72.2	
	292.2		Z86.41	
	292.9		F11*	
	292.11		F14*	
	292.12		F15*	
	292.81		F19*	
	292.82		T40*	
	292.83		Z78.9	
	292.84		Z21*	
	292.85		B24*	
	292.89		Z59*	
	304.00			
	304.01			
	304.02			
	304.03			
	304.20			
	304.21			
	304.22			
	304.23			
	304.40			

(Continued)

TABLE E1. Continued

Diagnosis/procedure	ICD-9-CM diagnosis codes	ICD-9-CM procedure codes	ICD-10-CM diagnosis codes	ICD-10-CM procedure codes
	304.41			
	304.42			
	304.43			
	304.60			
	304.61			
	304.62			
	304.63			
	305.50			
	305.51			
	305.52			
	305.53			
	305.60			
	305.61			
	305.62			
	305.63			
	305.70			
	305.71			
	305.72			
	305.73			
	305.90			
	305.91			
	305.92			
	305.93			
	E850.0			
	E850.1			
	E850.2			
	E935.0			
	E935.1			
	E935.2			
	E940.1			
	970.1			
	965.09			
	965.02			
	965.01			
	965.00			
	304.70			
	304.71			
	304.72			
	304.73			
Smoking	305.1		F17.2*	
	V15.82		Z87.891	
Cardiac complications	997.1		I97.1*	
	785.51		I97.3	
	427.41		T81.11*	

(Continued)

TABLE E1. Continued

Diagnosis/procedure	ICD-9-CM diagnosis codes	ICD-9-CM procedure codes	ICD-10-CM diagnosis codes	ICD-10-CM procedure codes
	427.5		R57.0	
	410*		I49.01	
			I46.9	
			I21*	
Respiratory complications	481		J95.1-J95.5	
	482*		J95.81*	
	518.5*		J95.82*	
	518.7		J95.831	
	518/81		J95.861	
	997.3*		J95.863	
			J95.89	
			J13*	
			J15*	
			J96.0*	
			J96.2*	
Renal complications/acute kidney injury	584*		N17*	
	997.5		N99.0	
Stroke	997.02		I97.82*	
Paralysis	342*		G81*	
	344.0*		G82*	
	344.1			
Spinal cord injury	952*		S14.10*	
	336.1		S24.10*	
			S34.10*	
			S34.139*	
			S34.3XXA	
			G95.1	

ICD-9-CM, International Classification of Diseases, Ninth Revision, Clinical Modification; *ICD-10-CM*, International Classification of Diseases, Tenth Revision, Clinical Modification. *Indicates inclusion of all subcategorical codes for given ICD code.