# All-cause procedural readmissions following transcatheter aortic valve replacement

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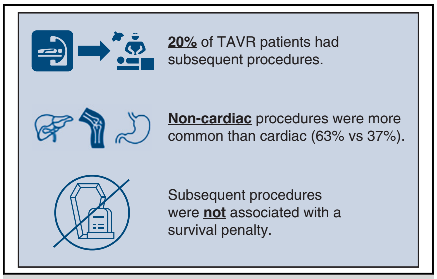
## ABSTRACT

**Objective:** With expanding eligibility criteria, transcatheter aortic valve replacement is being performed on patients with longer life expectancy, and subsequent procedures after index transcatheter aortic valve replacement are inevitable. This study examines the incidence and outcomes of patients undergoing subsequent procedural readmissions after transcatheter aortic valve replacement.

**Methods:** All patients who underwent index transcatheter aortic valve replacement and were discharged alive from January 2012 to December 2019 at a single institution were evaluated. Study end points were mortality and readmission for procedure with more than 1-day hospital stay. Effect on survival was evaluated by treating procedural readmission as a time-dependent variable by Cox proportional hazard model and competing risk analysis.

**Results:** A total of 1092 patients met inclusion criteria with a median follow-up time of 34 months. A total of 218 patients (20.0%) had 244 subsequent procedural readmissions. During the 244 procedural readmissions, there were 260 procedures; 96 (36.9%) were cardiac (most commonly pacemaker implantation, percutaneous coronary interventions, and surgical aortic valve replacements), and 164 (63.1%) were noncardiac (most commonly orthopedic and gastrointestinal procedures). The overall procedural readmission rates were 32%, 39%, and 42%, and all-cause mortality was 27%, 44%, and 54% at 20, 40, and 60 months, respectively. Procedural readmissions were not associated with a survival penalty in any surgical risk group or on Cox regression (hazard ratio, 1.25; 0.91-1.64, $P = .17$).

**Conclusions:** After transcatheter aortic valve replacement, procedural interventions are seen frequently, with most procedures occurring within the first year after transcatheter aortic valve replacement. However, subsequent procedural readmissions do not appear to have a survival penalty for patients after transcatheter aortic valve replacement. After transcatheter aortic valve replacement with resolution of aortic stenosis, subsequent procedures can and should be pursued if they are needed. (JTCVS Open 2023;15:83-93)




No survival penalty over 5-year follow-up for procedural readmission after TAVR.

**CENTRAL MESSAGE**

After TAVR, procedural readmissions occur in 20% of patients, with 65% noncardiac and 35% cardiac procedures, but are not associated with a survival penalty.

**PERSPECTIVE**

One of the first studies to examine the incidence and impact of cardiac and noncardiac procedural readmissions after TAVR demonstrates that procedural readmissions are common, more often noncardiac, and not associated with a survival penalty. As TAVR expands to a younger population, subsequent procedures after TAVR should be pursued if necessary.

With expanding eligibility criteria, transcatheter aortic valve replacement (TAVR) is being performed on an increasing number of patients, with 58,657 TAVRs performed in the United States in 2018,[1] and TAVRs surpassed the number of surgical aortic valve replacements (SAVRs) in 2019.[1,2] Although severe aortic stenosis (AS)

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**Abbreviations and Acronyms**

| | |
|---|---|
| AS | = aortic stenosis |
| HR | = hazard ratio |
| PCI | = percutaneous coronary intervention |
| SAVR | = surgical aortic valve replacement |
| STS-PROM | = Society of Thoracic Surgeons Predicted Risk of Mortality |
| TAVR | = transcatheter aortic valve replacement |

was once a terminal diagnosis, now patients who undergo an aortic valve replacement have near restoration of their life expectancy.[3,4] With more patients undergoing TAVR, and promising short-, mid-, and long-term outcomes,[5-10] patients undergoing TAVR are living longer, and subsequent procedural interventions after index TAVR are inevitable.

In the United States, an individual with an 85-year lifetime will require an average of 9.2 procedures,[11] and approximately half of all surgical procedures performed are on patients aged more than 65 years.[12,13] AS has long been associated with worse perioperative outcomes[14-16] and increased perioperative mortality.[14,17,18] As a result, the American Heart Association/American College of Cardiology treatment guidelines recommend postponing surgery, particularly noncardiac surgery, until after treatment of AS with SAVR or TAVR.[19-21] The combination of the high frequency of procedures, increased prevalence of AS, and recommendations for preoperative treatment of AS makes understanding the incidence and outcomes of subsequent procedures in patients with prior TAVR critical. The few studies that have examined subsequent procedural interventions after TAVR primarily focus on valve reintervention,[9,22] but to our knowledge there is no study that has examined both cardiac and noncardiac procedural interventions in patients with a prior TAVR. This study is one of the first to examine the incidence and outcomes of patients undergoing subsequent procedures after index TAVR.

## MATERIALS AND METHODS

The Mass General Brigham Institutional Review Board initially approved the study on February 9, 2010, under expedited review with waived consent (Protocol #2010P000292). All analyses were conducted using SPSS versions 26.0 and 27.0 (IBM Corp) or R version 3.4.1 (R Foundation).

### Study Design and Population

All consecutive adult patients who underwent index TAVR at a single institution from January 2012 to December 2019 were considered for the study (N = 1415). Patients who were discharged alive but had previous valve surgery (N = 299) or incomplete records (N = 24) were excluded. Patients with operative mortality after index TAVR were not included because they were not at risk for procedural readmission. We performed a retrospective review of prospectively collected institutional data to identify all eligible patients using procedure and billing codes. To identify the subset of patients who had procedural readmissions, we identified the subsequent cardiac and noncardiac procedures using diagnosis-related groups through extracted data from the hospital's electronic medical records' discharge abstracts.

### Variables and Outcomes of Interest

Patient demographics, laboratory values, operative details, and in-hospital outcomes were obtained from the patients' electronic medical records. Data on long-term outcomes were collected through routine patient or clinic follow-up, our internal research data repository, or by query of our institution's Healthcare Research Patient Data Repository, which contains National Death Index data. Follow-up time was calculated in days from the date of index TAVR to the date of death, procedural readmission, or end of the study observation (7/31/2021). All variables collected were coded according to the STS/ACC Transcatheter Valve Therapy Registry[23] (version 2.1) specifications unless otherwise noted. Operative mortality included any death occurring in the hospital or within 30 days of surgery if discharged alive. The main outcome of interest was readmissions for procedures using abstracted discharge summaries containing International Classification of Diseases Version 10 and Current Procedural Terminology coding, as well as demographic and administrative information. A length of stay threshold of more than 1 day was chosen a priori to exclude day surgery or in-office procedures. The case status of procedures (elective vs nonelective) was determined by the specific diagnosis-related group that designates that the procedure was not elective; if that was not available, patients who were admitted at least 1 day before the procedure were classified as nonelective. Only subsequent procedures that occurred in a separate hospital admission were included in the procedural readmission group; consequently, any procedures that occurred during the index TAVR admission were not counted as procedural readmissions. For the subgroup analysis, only the first readmission was counted to group patients as having cardiac or noncardiac readmissions. The secondary outcome of interest was survival.

### Statistical Analysis

Categorical variables are presented as frequency and percentages, and continuous variables are presented as mean/standard deviation or median/interquartile range as appropriate. Categorical variables were compared using Fisher exact tests, and Student *t* tests or log-rank tests were used for continuous variables depending on the distribution. Cumulative percent without events for both survival and procedural readmissions was estimated by Kaplan–Meier analyses and the Fine-Gray method for competing risks. An initial univariate Cox proportional hazards model with time to readmission as a time-dependent variable was run to evaluate the presence of a "wait-time" survivor bias for the procedural reintervention groups.

A second multivariable, forward-entry Cox model was used to evaluate the adjusted effect of procedural readmissions on survival, treating procedural readmissions as a time-dependent variable, including testing for the interaction between type of reintervention and time. Variables included in this model were selected on the basis of association with mortality on exploratory analyses, clinical importance to patient outcomes or association with readmission, and those that differed significantly between groups.

## RESULTS

A total of 1092 patients met inclusion criteria, with a total of 390 deaths and 218 patients with procedural readmissions (total of 244 readmissions with 260 total procedures performed) during the study period. Overall median

**TABLE 1. Baseline characteristics of patients with and without subsequent procedural readmissions* after index transcatheter aortic valve replacement**

| Characteristics | Overall [N = 1092] | Procedural readmission [N = 218] | No procedural readmission [N = 874] | *P* value† |
|---|---|---|---|---|
| Demographics | | | | |
| Age, y [Mean, SD] | 79.1 (9.3) | 78.0 (9.7) | 79.4 (9.1) | .051 |
| Age ≥85 y | 290 (26.6%) | 50 (22.9%) | 240 (27.5%) | .20 |
| Female | 484 (44.3%) | 106 (48.6%) | 378 (43.2%) | .17 |
| Moderate/severe lung disease | 159 (14.6%) | 35 (16.1%) | 124 (14.2%) | .52 |
| Diabetes | 365 (33.4%) | 68 (31.2%) | 297 (34.0%) | .47 |
| Dialysis | 33 (3.0%) | 11 (5.0%) | 22 (2.5%) | .07 |
| Cerebrovascular disease | 182 (16.7%) | 34 (15.6%) | 148 (16.9%) | .60 |
| Previous stroke | 111 (10.2%) | 19 (8.7%) | 92 (10.5%) | .53 |
| Peripheral vascular disease | 320 (29.3%) | 73 (33.5%) | 247 (28.3%) | .14 |
| Angina | 60 (5.5%) | 16 (7.3%) | 44 (5.0%) | .54 |
| Prior myocardial infarction | 232 (21.2%) | 46 (21.1%) | 186 (21.3%) | .99 |
| Previous atrial fibrillation | 425 (38.9%) | 82 (37.6%) | 343 (39.2%) | .70 |
| Congestive heart failure within 2 wk | 565 (51.7%) | 121 (55.5%) | 444 (50.8%) | .23 |
| NYHA class III/IV | 82 (7.5%) | 22 (10.1%) | 60 (6.9%) | .19 |
| Ejection fraction percent [Median, IQR] | 60 [50, 65] | 60 [50, 65] | 60 [50, 65] | .69 |
| STS-PROM [Mean, SD] | 4.78 (3.73) | 5.27 (3.72) | 5.04 (3.74) | .44 |
| Echocardiographic and operative data from index TAVR | | | | |
| Urgent/emergency status | 126 (11.5%) | 26 (11.9%) | 100 (11.4%) | .86 |
| Hostile chest | 63 (5.8%) | 16 (7.3%) | 47 (5.4%) | .26 |
| Previous procedures | | | | |
| Coronary artery bypass grafting | 216 (19.8%) | 37 (17.0%) | 179 (20.5%) | .26 |
| Aortic valve procedure | 133 (12.2%) | 31 (14.2%) | 102 (11.7%) | .30 |
| Valve etiology | | | | .74 |
| Congenital | 22 (2.0%) | 2 (0.9%) | 20 (2.3%) | |
| Degenerative | 1038 (95.1%) | 209 (95.9%) | 829 (94.9%) | |
| Rheumatic | 4 (0.4%) | 1 (0.5%) | 3 (0.3%) | |
| Other | 28 (2.6%) | 6 (2.8%) | 22 (2.5%) | |
| Mean aortic valve gradient in mm Hg [Mean, SD] | 42.0 (14.5) | 42.3 (13.1) | 43.0 (13.4) | .44 |
| Peak aortic valve gradient in mm Hg [Mean, SD] | 68.6 (22.9) | 70.0 (20.8) | 71.0 (20.9) | .53 |
| Aortic valve area in $cm^2$ [Mean, SD] | 0.77 (0.19) | 0.73 (0.18) | 0.72 (0.18) | .26 |
| Indications for TAVR | | | | .22 |
| Aortic insufficiency | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | |
| Aortic stenosis | 1053 (96.4%) | 213 (97.7%) | 840 (96.1%) | |
| Aortic insufficiency and stenosis | 12 (1.1%) | 0 (0.0%) | 12 (1.4%) | |
| Structural valve degeneration | 27 (2.5%) | 5 (2.3%) | 22 (2.5%) | |
| Postoperative outcomes from index TAVR | | | | |
| Red blood cell transfusion | 97 (8.9%) | **29 (13.3%)** | 68 (7.8%) | **.02** |
| Discharged to rehabilitation | 207 (19.0%) | **55 (25.2%)** | 152 (17.4%) | **.01** |
| Follow-up time, mo [Median, IQR] | 34 [22, 49] | - | - | - |

All values presented as N (%) unless otherwise specified. Values in bold signify those with a *P*-value <.05. *SD*, Standard deviation; *NYHA*, New York Heart Association; *IQR*, interquartile range; *STS-PROM*, Society of Thoracic Surgeons Predicted Risk of Mortality Score; *TAVR*, transcatheter aortic valve replacement. *Patients are categorized based on first procedural readmission if multiple. †*P* value compares the procedural readmission group with the no procedural readmission group.

follow-up time was 34 months (interquartile range, 22-49 months), with 6 patients (1.5%) lost to follow-up and truncated at last known clinical contact.

### Baseline Characteristics of Patients With and Without Procedural Readmissions

The overall mean age was 79.1 years, 484 patients (44.3%) were female, and mean Society of Thoracic Surgeons Predicted Risk of Mortality (STS-PROM) score was 4.8%. A total of 218 patients (20.0%) had a subsequent procedural readmission during the study period. Patients who had procedural readmissions were similar in age, gender, comorbidity burden, and STS-PROM score to those who did not have procedural readmissions. Full baseline characteristics of patients with versus without procedural readmissions are presented in Table 1.

**TABLE 2. Baseline characteristics of patients with cardiac versus noncardiac procedural readmissions* after index transcatheter aortic valve replacement**

| Characteristics | Cardiac procedural readmission patients [N = 77] | Noncardiac procedural readmission patients [N = 141] | *P* value |
|---|---|---|---|
| Demographics | | | |
| Age, y [Mean, SD] | 77.5 (10.3) | 78.3 (9.4) | .57 |
| Age ≥85 y | 21 (27.3%) | 29 (20.6%) | .31 |
| Female | 28 (36.4%) | **78 (55.3%)** | **.011** |
| Moderate/severe lung disease | 11 (14.3%) | 24 (17.0) | .70 |
| Diabetes | 26 (33.8%) | 42 (29.8%) | .65 |
| Dialysis | 3 (3.9%) | 8 (5.7%) | .75 |
| Cerebrovascular disease | 17 (22.1%) | 17 (12.1%) | .07 |
| Previous stroke | 10 (13.0%) | 9 (6.4%) | .13 |
| Peripheral vascular disease | 24 (31.2%) | 49 (34.8%) | .65 |
| Angina | 8 (10.4%) | 8 (5.7%) | .25 |
| Prior myocardial infarction | 18 (23.4%) | 28 (19.9%) | .60 |
| Previous atrial fibrillation | 31 (40.3%) | 51 (36.2%) | .66 |
| Congestive heart failure within 2 wk | 47 (61.0%) | 74 (52.5%) | .26 |
| NYHA Class III/IV | 8 (10.4%) | 14 (9.9%) | .46 |
| Ejection fraction percent [Median, IQR] | 50 [45, 60] | 60 [43, 65] | .29 |
| STS-PROM [Mean, SD] | 4.8 (3.7) | 5.6 (3.7) | .17 |
| Echocardiographic and operative data from index TAVR | | | |
| Urgent/emergency status | 8 (10.4%) | 18 (12.8%) | .69 |
| Hostile chest | 4 (5.2%) | 12 (8.5%) | .43 |
| Previous procedures | | | |
| Coronary artery bypass grafting | 13 (16.9%) | 24 (17.0%) | >.99 |
| Aortic valve procedure | 9 (11.7%) | 22 (15.6%) | .54 |
| Valve etiology | | | .53 |
| Congenital | 0 (0%) | 2 (1.4%) | |
| Degenerative | 74 (96.1%) | 125 (88.7%) | |
| Rheumatic | 3 (3.9%) | 3 (2.1%) | |
| Other | 0 (0%) | 1 (0.7%) | |
| Mean aortic valve gradient in mm Hg [Mean, SD] | 42.0 (14.5) | 42.4 (12.3) | .82 |
| Peak aortic valve gradient in mm Hg [Mean, SD] | 68.6 (22.9) | 70.7 (19.6) | .37 |
| Aortic valve area in $cm^2$ [Mean, SD] | **0.77 (0.2)** | 0.71 (0.2) | **.014** |
| Indications for TAVR | | | .054 |
| Aortic insufficiency | 0 (0%) | 0 (0%) | |
| Aortic stenosis | 73 (94.8%) | 140 (99.3%) | |
| Aortic insufficiency and stenosis | 0 (0%) | 0 (0%) | |
| Structural valve degeneration | 4 (5.2%) | 1 (0.7%) | |
| Postoperative outcomes from index TAVR | | | |
| Red blood cell transfusion | 7 (9.1%) | 22 (15.6%) | .21 |
| Discharged to rehabilitation | 19 (24.7%) | 36 (25.5%) | .31 |
| Follow-up time, mo [Median, IQR] | 44 [25, 56] | 39 [24, 56] | .41 |

All values presented as N (%) unless otherwise specified. Values in bold signify those with a *P*-value <.05. *SD*, Standard deviation; *NYHA*, New York Heart Association; *IQR*, interquartile range; *STS-PROM*, Society of Thoracic Surgeons Predicted Risk of Mortality Score; *TAVR*, transcatheter aortic valve replacement. *Patients are categorized based on first procedural readmission if multiple.

### Baseline Characteristics of Patients With Cardiac Versus Noncardiac Procedural Readmissions

Of the 218 patients who had procedural readmissions, 77 (35.3%) underwent cardiac procedures and 141 (64.7%) underwent noncardiac procedures. There were fewer female patients who underwent cardiac procedures than noncardiac procedures (36.4% vs 55.3%, $P = .01$), but otherwise, baseline characteristics were similar between groups. Full baseline characteristics for cardiac versus noncardiac procedural readmissions are presented in Table 2.

### Procedural Characteristics and Outcomes

There were 244 procedural readmissions, with 90 (36.9%) classified as cardiac and 154 (63.1%) classified as noncardiac based on the first procedure performed in the hospitalization. There were 260 total procedures performed; 96 were cardiac procedures, and 164 were noncardiac procedures. Of

**TABLE 3. Type of procedure and procedural outcomes for patients with procedural readmissions after index transcatheter aortic valve replacement**

| Characteristics | Overall procedures [N = 260] | Cardiac procedures [N = 96] | Noncardiac procedures [N = 164] |
|---|---|---|---|
| Time to procedure, mo [Median, IQR] | 7.0 [1, 20] | 10.0 [0.25, 22.5] | 6 [1.0, 18.0] |
| No. of patients with ≥1 procedure | 24/218 (11.0%) | - | - |
| Time interval for first subsequent procedure from index TAVR | | | |
| 0-7 d | 2/218 (0.9%) | 2/77 (2.6%) | 0/141 (0%) |
| 8-30 d | 5/218 (2.3%) | 1/77 (1.3%) | 4/141 (2.8%) |
| 31 d to y | 57/218 (26.1%) | 7/77 (9.1%) | 50/141 (35.5%) |
| >1 y | 154/218 (70.6%) | 67/77 (87.0%) | 87/141 (61.7%) |
| Type of procedure | | | |
| Permanent pacemaker implantation | 41 (15.8%) | 41 (42.7%) | - |
| PCI | 18 (6.9%) | 18 (18.8%) | - |
| Surgical aortic valve replacement | 10 (3.8%) | 10 (10.4%) | - |
| Repeat TAVR | 8 (3.1%) | 8 (8.3%) | - |
| Mitral valve surgery | 7 (2.7%) | 7 (7.3%) | - |
| Atrial septal defect closure | 5 (1.9%) | 5 (5.2%) | |
| Coronary artery bypass graft | 2 (0.8%) | 2 (2.1%) | - |
| Ascending aorta surgery | 2 (0.8%) | 2 (2.1%) | - |
| Mitral transcatheter edge-to-edge repair | 1 (0.4%) | 1 (1.0%) | - |
| Transcatheter mitral valve replacement | 1 (0.4%) | 1 (1.0%) | - |
| Ventricular assist device placement | 1 (0.4%) | 1 (1.0%) | |
| Tricuspid valve surgery | 0 (0%) | 0 (0%) | - |
| Pulmonary valve surgery | 0 (0%) | 0 (0%) | - |
| Elective orthopedic surgery | 20 (7.7%) | - | 20 (12.2%) |
| Nonelective GI surgery | 19 (7.3%) | - | 19 (11.6%) |
| Nonelective orthopedic surgery | 18 (6.9%) | - | 18 (11.0%) |
| Nonelective endoscopic GI bleeding control | 16 (6.2%) | - | 16 (9.8%) |
| Nonelective vascular surgery | 15 (5.8%) | - | 15 (9.1%) |
| Nonelective other surgery | 11 (4.2%) | - | 11 (6.7%) |
| Elective malignancy surgery | 10 (3.8%) | - | 10 (6.1%) |
| Nonelective malignancy surgery | 9 (3.5%) | - | 9 (5.5%) |
| Elective GI surgery | 9 (3.5%) | - | 9 (5.5%) |
| Elective neurosurgery | 9 (3.5%) | - | 9 (5.5%) |
| Elective minimally invasive lung surgery | 8 (3.1%) | - | 8 (4.9%) |
| Nonelective lung surgery | 5 (1.9%) | - | 5 (3.0%) |
| Nonelective neurosurgery | 4 (1.5%) | - | 4 (2.4%) |
| Nonelective wound debridement | 3 (1.2%) | - | 3 (1.8%) |
| Bariatric surgery | 2 (0.8%) | - | 2 (1.2%) |
| Elective other surgery | 2 (0.8%) | - | 2 (1.2%) |
| Nonelective amputation | 2 (0.8%) | - | 2 (1.2%) |
| Elective infection control surgery | 1 (0.4%) | - | 1 (0.6%) |
| Elective vascular surgery | 1 (0.4%) | - | 1 (0.7%) |
| Postprocedure outcomes | | | |
| Length of stay, d [Median, IQR] | - | 2 [1, 5] | 2 [1, 6] |
| Patients who died within 30 d of procedure | 12/218 (5.5%) | 5/77 (6.5%) | 7/141 (5.0%) |

All values presented as N (%) unless otherwise specified. *IQR*, Interquartile range; *TAVR*, transcatheter aortic valve replacement; *PCI*, percutaneous coronary intervention; *GI*, gastrointestinal.

the cardiac procedures, the most common were pacemaker implantation (42.7%), percutaneous coronary intervention (PCI) (18.8%), SAVR (10.4%), and repeat TAVR (8.3%). Of the noncardiac procedures, the most common were elective orthopedic surgery (12.2%), nonelective gastrointestinal surgery (11.6%), nonelective orthopedic surgery (11.0%), and nonelective endoscopy for gastrointestinal bleeding (9.8%). There were 5 (6.5% of patients) deaths within 30 days of the cardiac procedures and 7 (5.0% of patients) deaths within 30 days of the noncardiac procedures. Full procedural characteristics and postoperative outcomes are presented in Table 3.

## Long-Term Outcomes and Cumulative Survival

After index TAVR, Kaplan–Meier estimate showed no difference in age-adjusted survival between patients who had procedural readmissions versus those who did not have procedural readmissions ($P = .87$) (Figure 1). A univariate Cox model with readmission as a time-dependent covariate also did not show an effect (hazard ratio [HR], 1.25 [0.91-1.64], $P = .17$). Upon further adjusted modeling, the type of reintervention was also not associated with any survival penalty ($P = .48$ for cardiac and .67 for noncardiac procedures). Significant contributors to mortality included age (HR, 1.02 for each year over age 79 years), peripheral vascular disease (HR, 1.30), dialysis (HR, 3.17), congestive heart failure (HR, 1.35), and atrial fibrillation (HR, 1.58) (all $P < .015$).

On competing risk analysis, the overall procedural readmission rates were 32%, 39%, and 42% at 20, 40, and 60 months post-TAVR, respectively, and the overall all-cause mortality was 27%, 44%, and 54% at 20, 40, and 60 months post-TAVR, respectively. Three years post-TAVR, the risk of death exceeds the risk of procedural readmissions (Figure 2).

## Subgroup Analysis: Cumulative Survival by Surgical Risk Group

A subgroup analysis was performed examining cumulative survival for the procedural readmission cohort and no procedural readmission cohort stratified by STS-PROM score into 3 surgical risk groups (low-risk = STS-PROM ≤3%; intermediate-risk = STS-PROM 3%-8%; high-risk = STS-PROM ≥8%). For patients both with and without procedural readmissions, patients with higher STS-PROM scores had worse survival than those with lower STS-PROM scores (Figure 3). When stratified by surgical risk group, there continued to be no survival penalty for procedural readmissions in the low-, intermediate-, or high-risk groups. The overall rates of procedural readmissions also did not differ between surgical risk groups ($P = .69$).

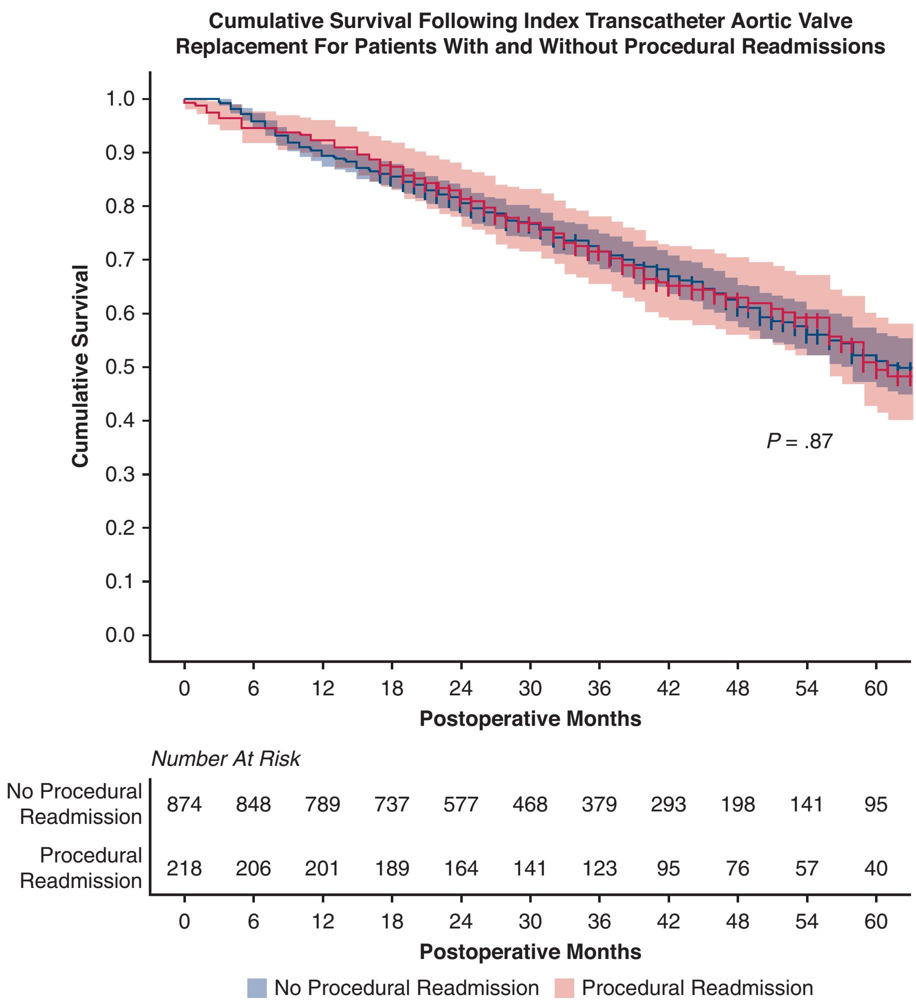


**FIGURE 1.** Cumulative survival after index TAVR for patients with versus without procedural readmissions. After index TAVR, there was no difference in age-adjusted survival between patients who did and did not have procedural readmissions ($P = .87$). Survival curve 95% confidence limit shown by *shading*.

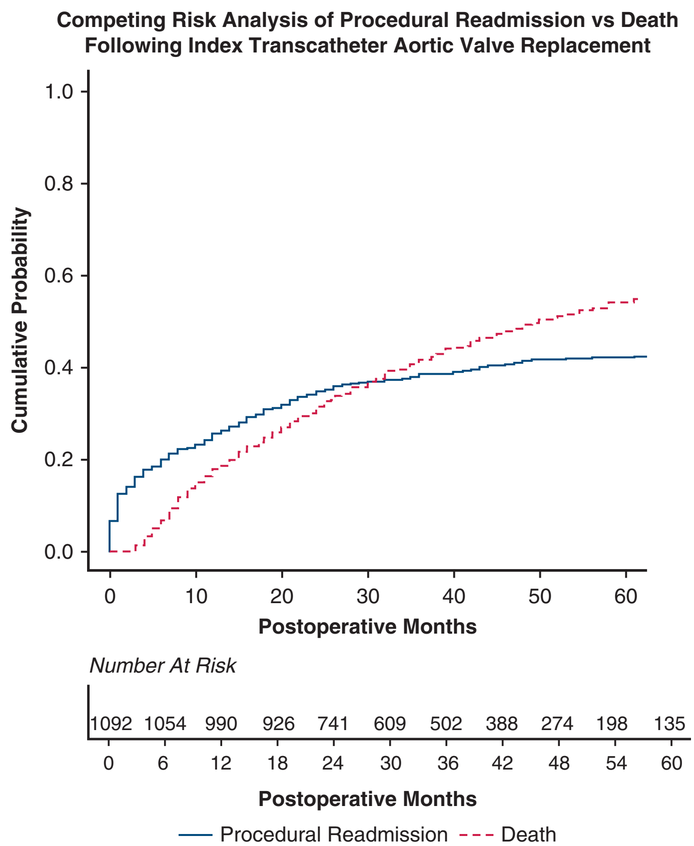


**FIGURE 2.** Competing risk analysis of procedural readmission versus death after index TAVR. After index TAVR, the overall procedural readmission rates were 32%, 39%, and 42% at 20, 40, and 60 months postoperatively, respectively. The overall all-cause mortality was 27%, 44%, and 54% at 20, 40, and 60 months postoperatively, respectively. Three years postoperatively, the risk of death exceeded the risk of readmission. *Curves* represent cumulative incidence functions for the probabilities of experiencing each of the competing risks at each point in time.

## DISCUSSION

In the first longitudinal study to examine the incidence and impact of subsequent cardiac and noncardiac procedures after index TAVR on patient outcomes, we report several important findings (Figures 4 and 5). First, subsequent procedures after index TAVR are common and occurred in 20% of patients, which is similar to the annual rate of surgery in older Americans.[13] Second, most procedural readmissions (65%) were noncardiac, with gastrointestinal and orthopedic surgeries being the most common noncardiac and minimally invasive procedures and aortic valve reinterventions being the most common cardiac procedures. Finally, there was no difference in survival between patients who did and did not undergo a subsequent procedure, which remained true after adjustment and when stratified by surgical risk group. These findings suggest that by correcting their AS, these patients can withstand subsequent procedures safely and emphasizes the importance of addressing AS before subsequent procedures.

Our study found that subsequent procedures after index TAVR occur in approximately 20% of patients, and by 5 years more than 40% of patients had undergone a procedure. The rate of procedural intervention in our post-TAVR cohort is similar to estimates of the rate of procedural interventions in older community-living Americans, with 8.8 surgeries being performed per 100 person-years.[13] This is likely a result of the improvement in our understanding and management of patients with severe AS over the last decade. AS has long been associated with worse perioperative outcomes after noncardiac surgery,[14-16] with up to a 10-fold increase in perioperative mortality compared with patients without AS.[14,17,18] However, with advancements in techniques, valve durability, and expanded eligibility criteria, severe AS no longer precludes noncardiac surgery but merely postpones it until after management via SAVR or TAVR.[8,19-21,24,25] Our results suggest that by correcting a patient's AS through TAVR, these patients can withstand subsequent procedures at a similar rate as the group without procedures, thus solidifying the importance of addressing AS before subsequent procedures in those with an indication for TAVR.[19] The combination of increased eligibility for TAVR and an increase in the older American population,

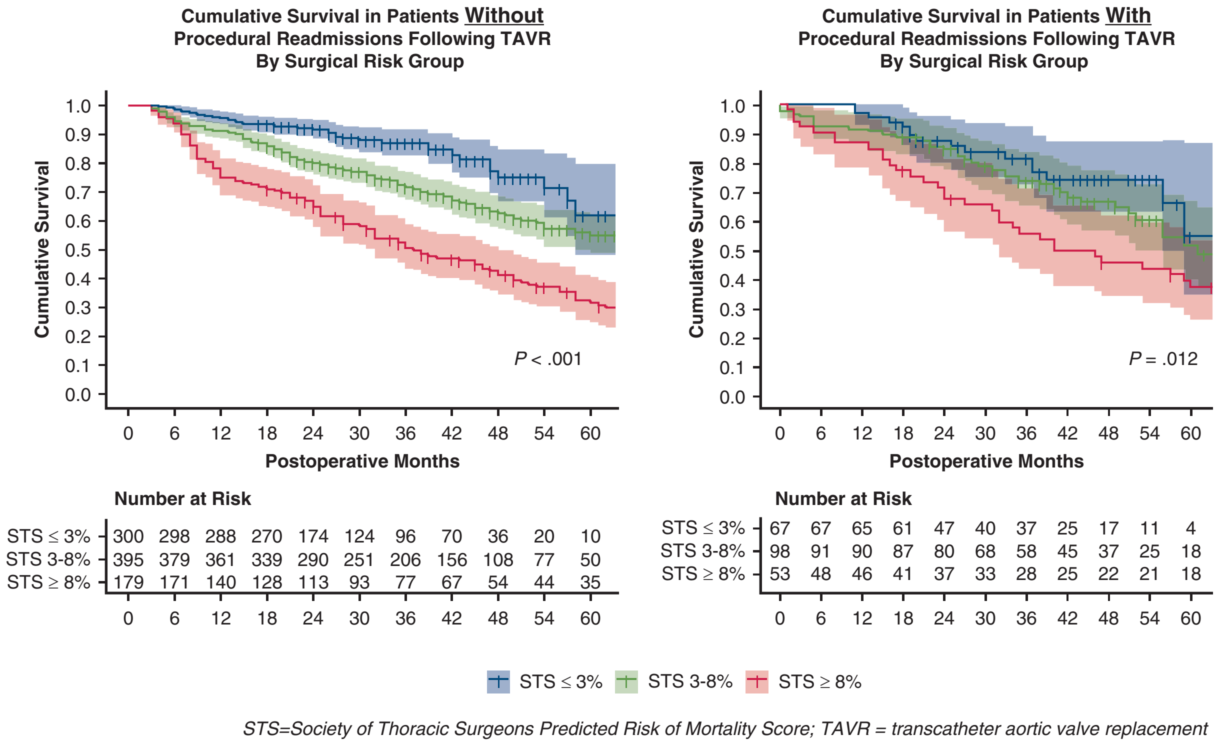


**FIGURE 3.** Cumulative survival after index TAVR for patients with and without procedural readmissions by surgical risk group. *Left*: cumulative survival for patients who did not have a procedural readmission after index TAVR stratified by the STS score. Patients with higher STS scores had worse survival ($P < .001$) than those with lower STS scores. *Right*: the same analysis but in patients who did have procedural readmissions after index TAVR. Patients with higher STS scores also had worse survival ($P = .012$) than those with lower STS scores. There continued to be no survival penalty for procedural readmissions in the 3 STS risk groups, and the overall rates of procedural readmission did not differ between risk groups ($P = .69$). Survival curve 95% confidence limit shown by *shading*. *TAVR*, Transcatheter aortic valve replacement; *STS*, Society of Thoracic Surgeons.

in whom AS is most prevalent, will undoubtedly lead to increasing rates of subsequent procedures after TAVR. Understanding the impact that TAVR has on any future procedure is critical and will only become more relevant as the population ages. In fact, approximately half of all surgical procedures in the United States are performed on patients aged more than 65 years, and projections estimate that half of the population aged more than 65 years will require surgery at least once.[12,13] The current literature largely focuses on the incidence and outcomes of cardiac procedures after TAVR; however, the impact that TAVR can have on future noncardiac procedures is also important and is more common than cardiac procedures. Our results suggest that if patients survive their index TAVR, subsequent surgeries are safe and not associated with increased mortality, which has implications for planned orthopedic or oncologic procedures.

Although the majority of subsequent procedures were noncardiac, subsequent cardiac procedures are of particular interest to the cardiothoracic surgeon and affected 35% of patients. This procedural breakdown is similar to the etiology of readmissions after both TAVR and SAVR, where it has been shown that 1 of 3 is due to cardiac causes.[26] The most common cardiac procedures after TAVR were pacemaker implantations, PCI, SAVR, and repeat TAVR. In our study, the subsequent procedures were not during the index TAVR admission and had to be associated with separate procedural readmission after TAVR discharge, so the odds that these procedures were a complication of the index TAVR are low. The only procedures that occurred within 1 week of index TAVR were 2 pacemaker implantations, which supports this. The majority of cardiac procedures occurred over 1 year after index TAVR. Our rates of subsequent cardiac procedures are similar to those identified in previous studies, whereby 5 years post-TAVR, 15.5% of patients had pacemaker implantations, and 3.2% had aortic valve reinterventions.[9] Delayed pacemaker implantation more often occurs during the same hospitalization of index TAVR rather than after discharge; however, with decreasing length of stay, there was been an increase in postdischarge pacemaker implantations in recent years,[27] which our study supports. PCI was the second most common cardiac procedure. Coronary access is feasible but can be technically difficult in patients post-TAVR especially for self-expandable valves or supra-annular valves,[28] and should be taken into consideration when performing index TAVR. Our

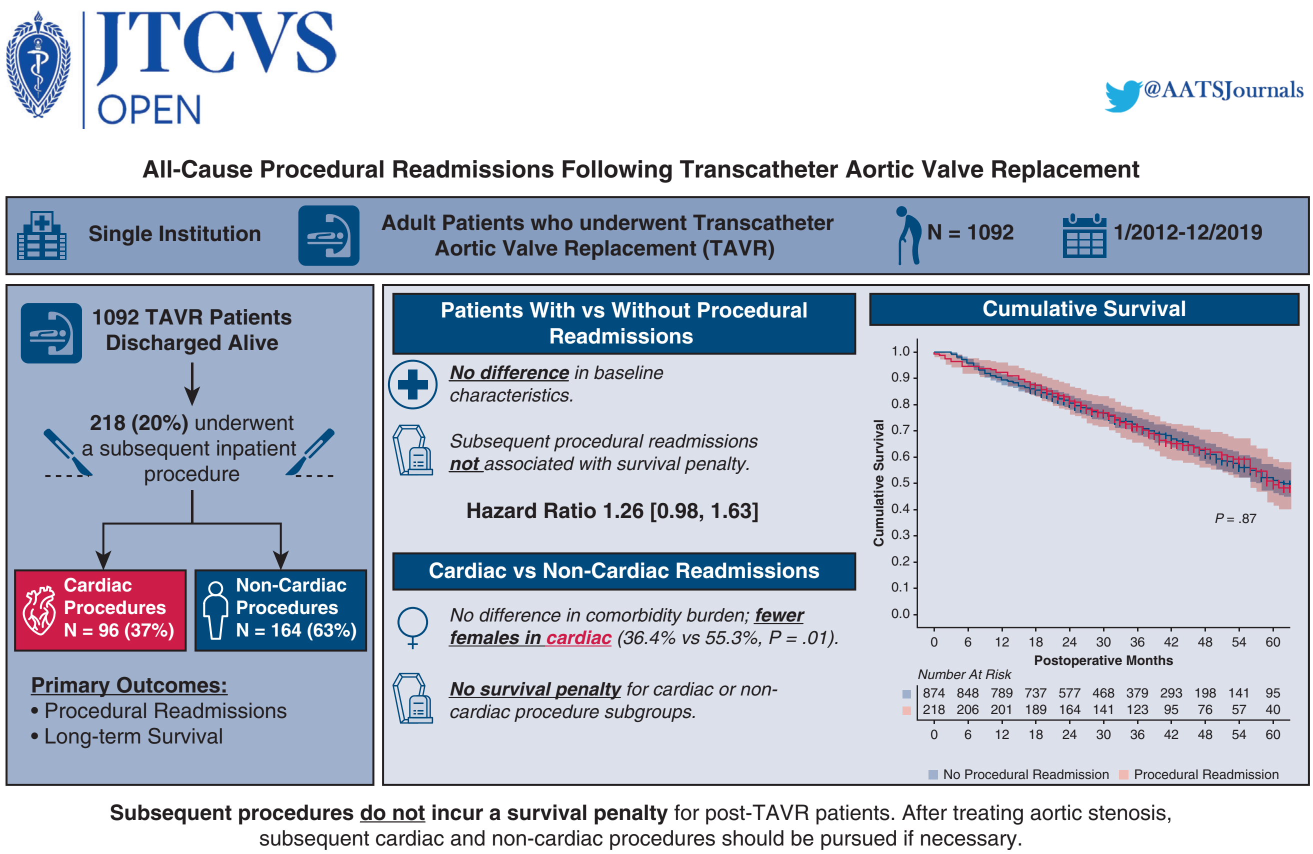


**FIGURE 4.** Graphical representation of this study's key findings.

institution considers concomitant treatment of coronary artery disease with high-risk and select intermediate-risk patients; however, the subsequent PCIs were in a separate hospital encounter than the index TAVR, and these patients may not have been candidates for earlier treatment. Finally, SAVR and repeat TAVR were the third and fourth most common procedures and were likely due to recurrent AS or new aortic insufficiency or paravalvular leak. Aortic valve reintervention is a known risk after index TAVR, and likely will be the main reinterventions for reintervention in the long term. Although subsequent cardiac procedures did not negatively impact survival, patients should have good surveillance when the need for these procedures can be identified before patients become older or higher risk.

More commonly occurring and rarely studied are the noncardiac procedures after index TAVR. Overall, the most common procedures were orthopedic procedures (15% of procedures) and gastrointestinal procedures (14% of procedures). Although 50% of the orthopedic surgeries were elective in nature, all of these gastrointestinal procedures were nonelective. Neither patients nor their cardiac surgeons anticipate needing those nonelective noncardiac procedures, so it is often an element that is overlooked when counseling patients on the risks and benefits of medical management, SAVR, and TAVR. When looking at the short-term procedures that occurred within 30 days of TAVR, they all were for malignancies. To our knowledge, our study is the first to specifically examine the outcomes after and types of noncardiac procedures in the post-TAVR population, and demonstrates that elective orthopedic surgeries, nonelective surgeries for trauma or

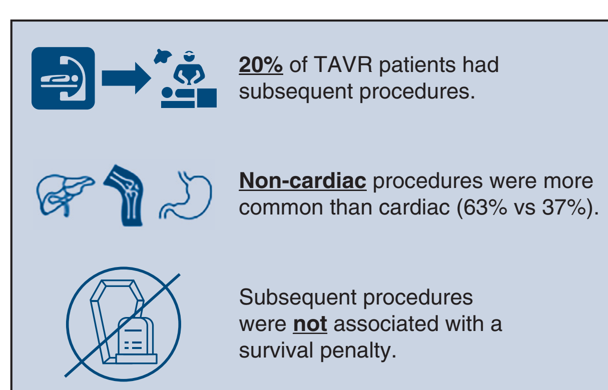


**FIGURE 5.** The study's key findings. *TAVR*, Transcatheter aortic valve replacement.

gastrointestinal bleeding, and planned malignancy operations can be safely pursued in patients post-TAVR.

Our study found that subsequent procedures after TAVR had no impact on patient survival, which remained true on adjusted analyses. As with all studies that examine competing risks, our findings must be interpreted within the limitations of selection and survival bias. There likely is a subgroup within the no procedural readmission group who may have benefitted from a procedure but were too sick/frail or elected not to receive the procedure, which could confound the results. Additionally, patients had to survive the index TAVR and be discharged to be included in the study, which inherently may select a healthier subpopulation. However, there was no difference in baseline characteristics or surgical risk score of the 2 groups. Moreover, in the adjusted analysis, the results remained consistent, even when accounting for surgical risk. Our cohort's overall mortality rate of 54% at 5 years is on par with national outcomes: The reported all-cause death rate of 46% at 5 years[9] post-TAVR in intermediate-risk patients is slightly lower likely because of our small sample size and 17% of our cohort was high risk, suggesting that the impact of survival bias was also low. This is further supported by our findings that procedural readmissions were not associated with a survival penalty in any risk group. Our findings suggest that patients undergoing TAVR, by treating the significant AS, are able to withstand the physiologic stressors of all types of future surgery safely without negatively impacting survival, which solidifies the importance of addressing AS before planned surgeries. As TAVR expands to a younger population, subsequent procedures can and should be pursued if needed in those patients with acceptable operative risk.

### Study Limitations

This study has several important limitations. First, this is a single institution study at a high-volume, academic, quaternary care center, and the generalizability of these results may be limited until validated using a larger sample. Additionally, this study only evaluated patients after the index TAVR, and the results may not be applicable to patients undergoing TAVR with prior aortic valve interventions. However, because this was a single-center study, we were able to collect granular variables and follow patients for both cardiac and noncardiac interventions, which would not be feasible using the currently available large, administrative, national databases. Further study on whether these results hold true based on operative approach or device type should be pursued. Second, there likely exists a subset of patients who may have qualified for a procedural intervention but ultimately did not undergo the procedure because of increased risk or patient choice. This concern is most relevant 3 years or more after the index TAVR, when the risk of death exceeded the risk of a subsequent procedure. This subset of patients cannot reliably be identified even with the granularity of a single-center study and may be a source of unmeasured confounding. Furthermore, with TAVR expanding to younger patients, our results may not be generalizable to the younger, lower-risk patients considering TAVR (given the mean age of our cohort was 79 years), and further study with this patient group should be pursued. Third, although we are able to report the time interval between the index TAVR and the subsequent procedure and the urgent versus elective case status, we are unable to comment on whether the subsequent procedure was planned before the index TAVR or an unanticipated event because of the retrospective nature of the study. Likewise, this study cannot comment on the indications for a reintervention or any index TAVR outcomes managed medically by the design of focusing on procedural interventions. Finally, although most patients who undergo TAVR at our institution choose to receive all their care at our institution, this current study is not able to capture procedural interventions that are performed out of network and thus may underestimate true procedural intervention rates. Despite these limitations, this study is still the first to report on the incidence and survival impact that subsequent procedural interventions have in the population post-TAVR.

## CONCLUSIONS

In the first study, to our knowledge, to examine the incidence and outcomes of both cardiac and noncardiac procedures in a post-TAVR population, we found that procedural interventions occur frequently, with more than 40% of patients undergoing a procedure within 5 years. Although 7% of patients overall underwent a cardiac procedure, approximately double that amount underwent noncardiac surgery. The burden of noncardiac procedures is significant in the TAVR population and should be considered in future research on readmissions and subsequent surgeries. Reassuringly, procedural readmissions did not negatively impact patient survival, which is encouraging evidence for the importance of addressing AS in a timely manner. Our results suggest that both nonelective and elective subsequent cardiac and noncardiac procedures can and should be pursued if needed post-TAVR in patients with acceptable operative risk.

### Conflict of Interest Statement

S.H. is a consultant for ERAS ENCARE. P.S. is a proctor for Edwards and receives educational grants from Edwards, Medtronic, and Abbott. T.K. is a consultant for Edwards Life Sciences, Medtronic, 4C Medical, Abbott, and Baylis. All other authors reported no conflicts of interest.

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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:** aortic valve replacement, outcomes, readmissions, subsequent procedures, TAVR, transcatheter