ORIGINAL RESEARCH

Association Between Patient Survival and Clinician Variability in Treatment Rates for Aortic Valve Stenosis

J. Matthew Brennan (iD), MD, MPH; Angela Lowenstern (iD), MD; Paige Sheridan (iD), MPH; Isabel J. Boero, MD, MS; Vinod H. Thourani, MD; Sreekanth Vemulapalli (iD), MD; Tracy Y. Wang, MD, MHS, MSc; Otto Liska, BA; Stuart Gander, BCom; Jason Jager, MS, MEng; Martin B. Leon, MD; Eric D. Peterson (iD), MD, MPH

BACKGROUND: Patients with symptomatic severe aortic stenosis (ssAS) have a high mortality risk and compromised quality of life. Surgical/transcatheter aortic valve replacement (AVR) is a Class I recommendation, but it is unclear if this recommendation is uniformly applied. We determined the impact of managing cardiologists on the likelihood of ssAS treatment.

METHODS AND RESULTS: Using natural language processing of Optum electronic health records, we identified 26 438 patients with newly diagnosed ssAS (2011–2016). Multilevel, multivariable Fine-Gray competing risk models clustered by cardiologists were used to determine the impact of cardiologists on the likelihood of 1-year AVR treatment. Within 1 year of diagnosis, 35.6% of patients with ssAS received an AVR; however, rates varied widely among managing cardiologists (0%, lowest quartile; 100%, highest quartile [median, 29.6%; 25th–75th percentiles, 13.3%–47.0%]). The odds of receiving AVR varied >2-fold depending on the cardiologist (median odds ratio for AVR, 2.25; 95% CI, 2.14–2.36). Compared with patients with ssAS of cardiologists with the highest treatment rates, those treated by cardiologists with the lowest AVR rates experienced significantly higher 1-year mortality (lowest quartile, adjusted hazard ratio, 1.22, 95% CI, 1.13–1.33).

CONCLUSIONS: Overall AVR rates for ssAS were low, highlighting a potential challenge for ssAS management in the United States. Cardiologist AVR use varied substantially; patients treated by cardiologists with lower AVR rates had higher mortality rates than those treated by cardiologists with higher AVR rates.

Key Words: aortic valve replacement ■ physician variability ■ symptomatic severe aortic stenosis

Symptomatic severe aortic stenosis (ssAS) is associated with a poor prognosis if left untreated. Aortic valve replacement (AVR) improves survival among patients with ssAS and is a Class IA recommendation by the American Heart Association/American College of Cardiology and European Society of Cardiology.[1] Although valve replacement was traditionally performed via open heart surgery (surgical AVR [SAVR]), the development of transcatheter AVR (TAVR) expanded options for AVR to the majority of patients with ssAS.[2–5] Yet despite the widespread availability of effective treatment options, barriers to treatment persist, and the contemporary penetrance of AVR remains unknown.[6,7]

Clinicians have a strong influence on the likelihood of many cardiovascular therapies, including amputation[8] in lower extremity peripheral arterial disease and the use of cardiac defibrillators[9] in heart failure. To date, the role of the managing cardiologist in shaping ssAS treatment has not been evaluated. In this analysis, we examined contemporary rates of AVR for the treatment of ssAS in the United States using the Optum database, which has been used for previous cardiac studies.[10,11] In addition, we evaluated clinician-level variation

CLINICAL PERSPECTIVE

What Is New?

- We identified patients with symptomatic severe aortic stenosis (ssAS) from a large database, evaluated the receipt of aortic valve replacement (AVR) within a year of ssAS diagnosis, and found that overall AVR rates for ssAS were low; the majority of patients with ssAS (64.4%) did not have an AVR within 1 year of diagnosis.
- AVR rates varied widely by managing cardiologist (>2-fold depending on cardiologist); patients with ssAS treated by cardiologists with lower AVR rates had higher mortality rates than those treated by cardiologists with higher AVR rates.

What Are the Clinical Implications?

- Given the availability of effective treatments, these findings underscore the need to implement targeted initiatives to raise disease awareness, promote more objective diagnostic criteria, and reduce barriers to treatment for patients with ssAS.

Nonstandard Abbreviations and Acronyms

AS	aortic stenosis
AVR	aortic valve replacement
MOR	median odds ratio
SAVR	surgical aortic valve replacement
ssAS	symptomatic severe aortic stenosis
TAVR	transcatheter aortic valve replacement

in the management of ssAS among cardiologists and its association with 1-year survival.

METHODS

Data Source

This retrospective study was conducted using Optum deidentified electronic health records (EHRs),[12] which is a patient-level database that aggregates EHR systems from >2000 US hospitals and 7000 clinics, including 82 million distinct patients, into a tabular format for research purposes. This data set is available through contract with Optum. Available information includes patient-level data from both the ambulatory and inpatient settings and provides unique identification numbers to physicians, allowing clinicians to be followed over time. The Optum database has been employed using similar methods from relevant previously published studies.[10,11]

Study Population

This study included patients newly diagnosed with ssAS between 2011 and 2016 within Optum's integrated delivery network, where care and coverage are offered through the same provider reducing the risk of missing records. Because the Optum data set does not routinely contain structured data elements for echocardiographic variables other than ejection fraction (Table S1), a review of physician notes was used to identify patients with severe aortic stenosis (AS).[13] Severe AS was defined by the inclusion of the terms *severe* or *critical* or a combination in the presence of the words *aortic stenosis*.[14–16] We excluded patients with neutral or negative terms associated with their AS diagnosis such as *negative*, *deny*, *not*, *suspect*, *potential*, or *rule out* or a combination thereof. Sensitivity analyses were performed to validate reported severity—a Kaplan–Meier analysis to stratify survival by AS grade and a review of 1206 patients with data for each of 3 metrics of aortic valve stenosis to evaluate correspondence with physician reports (Figure S1, Data S1, Tables S2 through S4). To address variability in the assignment of AS severity (particularly among low flow, low gradient cases), a sensitivity analysis was conducted limiting the analysis to patients with recorded left ventricular ejection fraction (LVEF) values, stratified by LVEF (LVEF <35, 35–49, <50, and ≥50).

Patients were classified as symptomatic if there were at least 2 positive entries for cardinal symptoms (heart failure, angina, dyspnea on exertion, dyspnea, presyncope, syncope) in the 6 months before severe AS diagnosis, similar to previously described methodologies.[15,17,18] Again, the use of negative terms was excluded from the symptomatic definition. Newly diagnosed patients with ssAS had either no documented history of severe AS within the year before their diagnosis or had severe AS, but no mention of symptoms in the 6 months before their diagnosis.

Included patients had at least 1 year of history in the EHR before ssAS diagnosis and at least 1 year of follow-up or a record of death in the year after the date of ssAS to allow for the evaluation of patient status. A total of 10 patients with a preexisting left ventricular assist device were excluded. An additional 11 461 patients without an identifiable managing cardiologist (defined in Exposure) were also excluded. The final cohort included 26 438 patients (Figure 1).

Risk-Adjustment Covariates

The risk-adjustment set was chosen a priori based on clinical factors that could impact the likelihood of treatment. Patient history was evaluated in the year before diagnosis using both *International Classification of Diseases, Ninth Revision, Clinical Modification* (*ICD-9-CM*) and *International Classification of Diseases,*
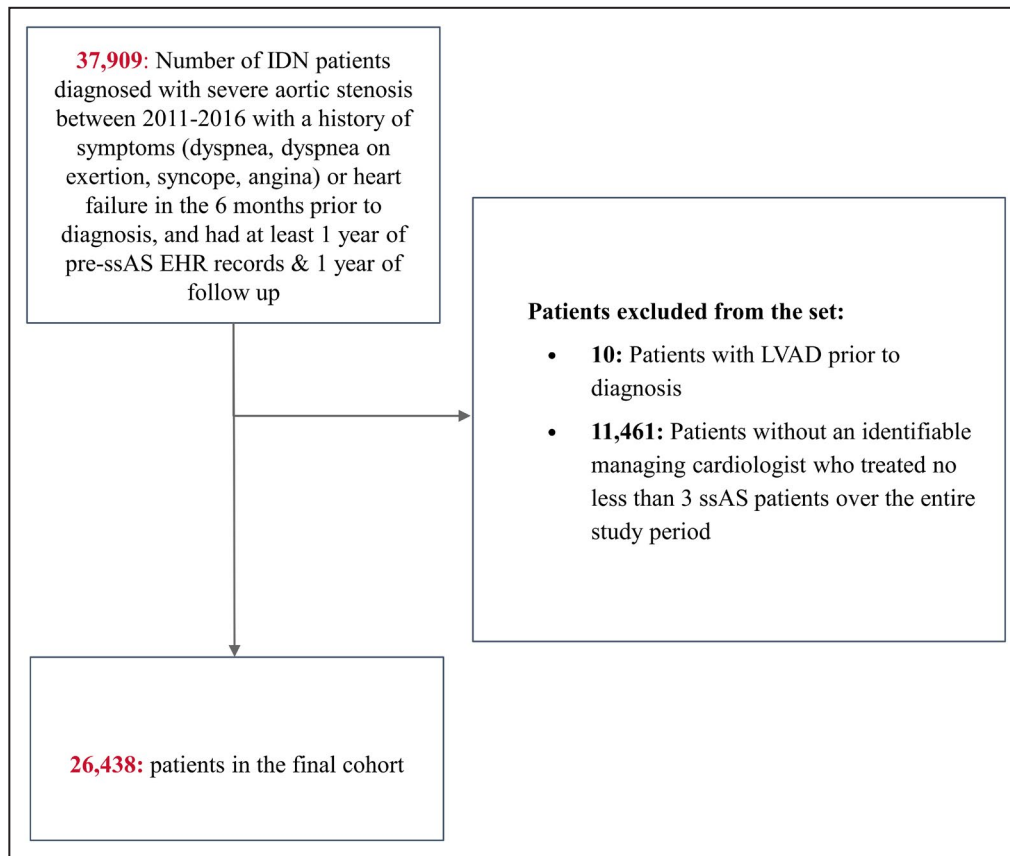
Figure 1. Modified consort diagram.
The 26 438 patients were managed by 1627 cardiologists. EHR indicates electronic health record; IDN, integrated delivery network; LVAD, left ventricular assist device; and ssAS, symptomatic severe aortic stenosis.

Tenth Revision, Clinical Modification (*ICD-10-CM*) codes with characteristics listed in Table. Records related to inpatient visits were reviewed to identify hospitalizations in the year before AS diagnosis and to determine the setting of the initial ssAS diagnosis. *ICD-9-CM/ICD-10-CM* and Current Procedural Terminology codes were used to assess select cardiac procedures and dialysis. Multimorbidity was assessed using the Deyo modification of the Charlson Comorbidity Index.[19] The full list of *ICD-9-CM* and *ICD-10-CM* codes used in this analysis is presented in Table S5. LVEF was obtained from structured extracts of echocardiography reports, as were patient age, sex, area income and education level, census region/division, insurance, and smoking status.

Exposure

A managing cardiologist for each patient with ssAS was identified in the Optum records using unique provider identification numbers and the reported specialty. The managing cardiologist was defined as the majority provider cardiologist most frequently seen by a patient

(as an inpatient or outpatient) in the 3 months before and after ssAS diagnosis. If multiple cardiologists met these criteria, then the cardiologist with visits closest to diagnosis was selected. We performed a sensitivity analysis focusing only on outpatient cardiologists to comment on the physician most likely responsible for long-term care (Data S2). Furthermore, to understand if an interventional subspecialty shaped treatment likelihood, we stratified cardiologists based on whether they performed percutaneous interventions.

Outcomes

The primary outcome of this study was treatment of ssAS using AVR (SAVR or TAVR) in the year following the first report of symptoms. Specific *ICD-9-CM/ICD-10-CM* and Current Procedural Terminology codes are listed in Table S5. In addition, we examined all-cause mortality at 1 year after diagnosis to evaluate the impact of provider treatment rates on patient outcomes. Date of death was captured in Optum using the Social Security Death Master File. Follow-up was evaluated through 2017.

Table. Patient Characteristics for the Overall Cohort and Stratified by Quartiles of AVR Treatment Rates by Managing Cardiologists

Patient characteristics	Overall, n=26 438	Quartiles of AVR treatment rates by managing cardiologists				P value
		First quartile lowest AVR, n=4257	Second quartile, n=7062	Third quartile, n=7138	Fourth quartile* highest AVR, n=7981	
Treatment in 1 y from first symptom report, n (%)						
SAVR	5894 (22.29)	146 (3.43)	1156 (16.37)	1902 (26.65)	2690 (33.70)	<0.001
TAVR	3513 (13.29)	58 (28.43)	412 (5.83)	736 (10.31)	2307 (28.91)	<0.001
SAVR or TAVR	9407 (35.58)	204 (4.79)	1568 (22.20)	2638 (36.96)	4997 (62.61)	<0.001
Sex, n (%)						
Female patient	12 140 (45.92)	2070 (48.63)	3313 (46.91)	3193 (44.73)	3564 (44.66)	<0.001
Age, y, n (%)						<0.001
Unknown	48 (0.18)	6 (0.14)	15 (0.21)	11 (0.15)	16 (0.20)	
<65	3685 (13.94)	665 (15.62)	960 (13.59)	1013 (14.19)	1047 (13.12)	
65–79	9892 (37.42)	1431 (33.62)	2635 (37.31)	2707 (37.92)	3119 (39.08)	
80+	12 813 (48.46)	2155 (50.62)	3452 (48.88)	3407 (47.73)	3799 (47.60)	
Charlson Comorbidity Index, n (%)						0.476
0	6821 (25.80)	1096 (25.75)	1813 (25.67)	1839 (25.76)	2073 (25.97)	
1	5657 (21.40)	903 (21.21)	1520 (21.52)	1470 (20.59)	1764 (22.10)	
2	4114 (15.56)	631 (14.82)	1114 (15.77)	1160 (16.25)	1209 (15.15)	
3	3287 (12.43)	534 (12.54)	863 (12.22)	892 (12.50)	998 (12.50)	
4+	6559 (24.81)	1093 (25.68)	1752 (24.81)	1777 (24.89)	1937 (24.27)	
Atrial fibrillation, n (%)	7521 (28.45)	1318 (30.96)	2135 (30.23)	2135 (29.91)	1933 (24.22)	<0.001
Cancer, n (%)	3408 (12.89)	478 (11.23)	870 (12.32)	990 (13.87)	1070 (13.41)	<0.001
Conduction, n (%)	2628 (9.94)	441 (10.36)	749 (10.61)	708 (9.92)	730 (9.15)	0.019
COPD, n (%)	2650 (10.02)	479 (11.25)	702 (9.94)	672 (9.41)	797 (9.99)	<0.001
Dementia, n (%)	607 (2.30)	133 (3.12)	186 (2.63)	157 (2.20)	131 (1.64)	<0.001
Diabetes mellitus without complications, n (%)	7401 (27.99)	1182 (27.77)	2021 (28.62)	1986 (27.82)	2212 (27.72)	0.597
Diabetes mellitus with complications, n (%)	1622 (6.14)	214 (5.03)	442 (6.26)	461 (6.46)	505 (6.33)	0.011
Prior MI, n (%)	3049 (11.53)	491 (11.53)	853 (12.08)	797 (11.17)	908 (11.38)	0.362
Osteoarthritis, n (%)	3756 (14.21)	624 (14.66)	1034 (14.64)	1018 (14.26)	1080 (13.53)	0.187
Peripheral vascular disease, n (%)	4164 (15.75)	609 (14.31)	1047 (14.83)	1170 (16.39)	1338 (16.76)	<0.001
Heart failure, n (%)	5535 (20.94)	940 (22.08)	1457 (20.63)	1538 (21.55)	1600 (20.05)	0.027
Moderate to severe renal disease, n (%)	5652 (21.38)	983 (23.09)	1522 (21.55)	1575 (22.07)	1572 (19.7)	<0.001
Current smoking, n (%)	2917 (11.03)	490 (11.51)	776 (10.99)	782 (10.96)	869 (10.89)	0.156
Use of supplemental oxygen, n (%)	1057 (4.00)	166 (3.90)	288 (4.08)	279 (3.91)	324 (4.06)	0.929
PCI, n (%)	583 (2.21)	75 (1.76)	131 (1.85)	134 (1.88)	243 (3.04)	<0.001
Pacemaker, n (%)	275 (1.04)	57 (1.34)	81 (1.15)	66 (0.92)	71 (0.89)	0.067
Hemodialysis, n (%)	379 (1.43)	86 (2.02)	103 (1.46)	96 (1.34)	94 (1.18)	0.002
Dyspnea, n (%)	23 910 (90.44)	3761 (88.35)	6320 (89.49)	6432 (90.11)	7397 (92.68)	<0.001
Dyspnea on exertion, n (%)	3941 (14.91)	616 (14.47)	1006 (14.25)	1027 (14.39)	1292 (16.19)	0.002
Angina, n (%)	7851 (29.70)	1269 (29.81)	2150 (30.44)	2029 (28.43)	2403 (30.11)	0.044
Syncope, n (%)	7183 (27.17)	1203 (28.26)	2012 (28.49)	1920 (26.90)	2048 (25.66)	<0.001
Ejection fraction, n (%)						<0.001
<35	2076 (7.85)	360 (8.46)	559 (7.92)	569 (7.97)	588 (7.37)	
35–49	2784 (10.53)	413 (9.70)	756 (10.71)	752 (10.54)	863 (10.81)	
50+	14 100 (53.33)	1914 (44.96)	3803 (53.85)	3904 (54.69)	4479 (56.12)	
Unknown	7478 (28.29)	1570 (36.88)	1944 (27.53)	1913 (26.80)	2051 (25.7)	

(Continued)

Table 1. Continued

Patient characteristics	Overall, n=26 438	Quartiles of AVR treatment rates by managing cardiologists				P value
		First quartile lowest AVR, n=4257	Second quartile, n=7062	Third quartile, n=7138	Fourth quartile* highest AVR, n=7981	
Creatinine, mg/dL, n (%)						<0.001
<1.0	8571 (32.42)	1282 (30.12)	2265 (32.07)	2306 (32.31)	2718 (34.06)	
1.0–1.4	8269 (31.28)	1250 (29.36)	2145 (30.37)	2286 (32.03)	2588 (32.43)	
1.5–1.9	2383 (9.01)	399 (9.37)	638 (9.03)	636 (8.91)	710 (8.90)	
2.0+	2053 (7.77)	410 (9.63)	567 (8.03)	556 (7.79)	520 (6.52)	
Unknown	5162 (19.52)	916 (21.52)	1447 (20.49)	1354 (18.97)	1445 (18.11)	
BMI, kg/m^2, n (%)						<0.001
<20.1	1248 (4.72)	276 (6.48)	344 (4.87)	298 (4.17)	330 (4.13)	
20.1–25.0	5970 (22.58)	1079 (25.35)	1616 (22.88)	1599 (22.40)	1676 (21.00)	
25.1–30.0	8331 (31.51)	1270 (29.83)	2252 (31.89)	2230 (31.24)	2579 (32.31)	
30.1+	9228 (34.90)	1358 (31.90)	2409 (34.11)	2590 (36.28)	2871 (35.97)	
Unknown	1661 (6.28)	274 (6.44)	441 (6.24)	421 (5.90)	525 (6.58)	
Diagnosed in inpatient	10 013 (37.87)	1881 (44.19)	2653 (37.57)	2720 (38.11)	2759 (34.57)	<0.001
Percent hospitalized in year prior	12 329 (46.63)	2214 (52.01)	3325 (47.08)	3351 (46.95)	3439 (43.09)	<0.001
Region, n (%)						<0.001
Midwest	13 332 (50.43)	1793 (42.12)	3684 (52.17)	3937 (55.16)	3918 (49.09)	
Northeast	3037 (11.49)	928 (21.80)	780 (11.05)	574 (8.04)	755 (9.46)	
Other/unknown	600 (2.27)	104 (2.44)	183 (2.59)	141 (1.98)	172 (2.16)	
South	6244 (23.62)	890 (20.91)	1571 (22.25)	1610 (22.56)	2173 (27.23)	
West	3225 (12.20)	542 (12.73)	844 (11.95)	876 (12.27)	963 (12.07)	
Year of diagnosis, n (%)						<0.001
2011–2012	5688 (21.51)	1041 (24.45)	1545 (21.88)	1651 (23.13)	1451 (18.18)	
2013–2014	8910 (33.7)	1520 (35.71)	2457 (34.79)	2352 (32.95)	2581 (32.34)	
2015–2016	11 840 (44.78)	1696 (39.84)	3060 (43.33)	3135 (43.92)	3949 (49.48)	
Insurance, n (%)						<0.001
Commercial	4914 (18.59)	769 (18.06)	1311 (18.56)	1282 (17.96)	1552 (19.45)	
Medicaid	673 (2.55)	105 (2.47)	151 (2.14)	241 (3.38)	176 (2.21)	
Medicare	13 089 (49.51)	2401 (56.4)	3676 (52.05)	3372 (47.24)	3640 (45.61)	
Other or unknown	7232 (27.35)	906 (21.28)	1755 (24.86)	2128 (29.81)	2443 (30.61)	
Uninsured	530 (2.00)	76 (1.79)	169 (2.39)	115 (1.61)	170 (2.13)	
Income level (25th, 75th percentiles)†	$40 125 ($35 814, $46 714)	$42 046 ($35 229, $47 758)	$40 125 ($35 268, $46 955)	$39 816 ($35 981, $44 376)	$40 550 ($35 020, $46 454)	<0.001
Percent college educated (25th, 75th percentiles)†	22.00 (18.00, 27.00)	23.00 (17.00, 29.00)	22.00 (19.00, 27.00)	22.00 (19.00, 27.00)	22.00 (18.00, 27.00)	<0.001

AVR indicates aortic valve replacement; BMI, body mass index; COPD, chronic obstructive pulmonary disease; MI, myocardial infarction; PCI, percutaneous coronary intervention; SAVR, surgical aortic valve replacement; and TAVR, transcatheter aortic valve replacement.

*The fourth quartile represents the highest treating clinicians.

†Area-level variable (zip 3).

Statistical Analyses

We compared patient characteristics across quartiles of observed AVR rates for managing cardiologists using chi-square tests. The quartiles were established via the PROC RANK SAS procedure, which assigns quartiles without ties, assigning the 0% treatment rate to the lowest quartile and then building the other quartiles based on patient numbers. This procedure can result in quartiles being of unequal size. For the initial assessment of the variability in treatment, we evaluated the observed and adjusted rates of AVR across quartiles of observed AVR rate using previously described methodology[20,21] and the multilevel model described in the next paragraph. Similar analysis was performed for TAVR.

The primary analysis in this study used a multivariable, multilevel, logistic model with the managing

cardiologist as the random intercept to assess the contribution of unique cardiologists on the likelihood of AVR at 1 year following ssAS diagnosis. The risk-adjustment set included variables presented in the Table. The median odds ratio (MOR)[22–24] was used to express the relative association of the managing cardiologist on the likelihood of AVR. The MOR expresses the likelihood of a patient receiving a different outcome if the patient were to switch to another randomly selected cardiologist. For example, a MOR of 1 would indicate no difference in the likelihood of AVR between managing cardiologists; however, a MOR of 1.5 would indicate a 50% greater odds of a different outcome if a patient was treated by another randomly selected cardiologist. A subsequent analysis examined the relative contribution of the cardiologist on receipt of TAVR compared with SAVR using similar methods. A sensitivity analysis was performed in a claims-linked set of 926 patients to confirm the results (Data S3) and in a patient subset with recorded ejection fraction, creatinine, and body mass index to better control for patient status (Data S4, Tables S6 and S7, and Figure S2). An additional sensitivity analysis was conducted to evaluate the impact of cardiologist caseload (which included both volume of patients with ssAS and AVR procedure volume) on the likelihood of AVR.

Kaplan–Meier curves were used to evaluate the survival associated with each quartile of AVR rates for managing cardiologists. Multilevel, multivariable Fine-Gray competing risk models clustered by cardiologists were used to determine the impact of cardiologists on the likelihood of 1-year AVR treatment. We adjusted for patient demographics and comorbidities listed in the Table. Subdistribution hazard ratios (HRs) were used to describe the impact of fixed covariates, and the MOR was used to describe the relative impact of the individual cardiologists on the likelihood of receiving the 1-year AVR treatment. A cubic spline was used to assess the proportional hazards assumption.[25] To model the relationship between cardiologist AVR treatment rate and 1-year all-cause mortality, the AVR rate was modeled as a restricted cubic spline with 4 degrees of freedom. A sensitivity analysis was performed to limit the impact of immortal time bias (Data S5). To evaluate the relative impact of cardiologists with high AVR rates on 1-year all-cause mortality, we conducted a sensitivity analysis by restricting the cohort to patients treated by cardiologists with AVR rates ≤70% (Data S6).

Imputation of missing variables with <10% of missing data was accomplished via multivariate imputation by chained equations using the version 2.9 package.[26] Details are found in Data S7. All analyses were conducted using SAS 9.4 and R version 3.5.2 with $P \leq 0.05$ considered significant.

Ethical/Institutional Review Board

We did not obtain ethical/institutional review board approval because this was a retrospective study of deidentified EHR data.

RESULTS

The study cohort of 26 438 patients with ssAS included 45.9% women with a median age of 79 years (25th–75th percentiles, 70–84 years) and median Charlson Comorbidity Index of 2 (25th–75th percentiles, 0–3). Median follow-up was 701 days (25th–75th percentiles, 395–1179 days). Dyspnea was the predominant symptom, affecting 90.4% of patients, with angina affecting 29.7% of patients. ssAS was primarily diagnosed in the outpatient setting (62.1%). Complete characteristics are presented in the Table.

Clinician Variability in AVR Use

The average general cardiologist saw a median of 10 newly diagnosed patients with ssAS during the study interval (25th–75th percentiles, 5–20). Within a year of the first report of symptoms, 35.6% of patients with ssAS underwent AVR (13.3% TAVR, 22.3% SAVR), and treatment rates increased from 26.8% in 2011 to 2012 to 40.9% for patients diagnosed in 2015 to 2016 (Figure 2).

Rates of AVR within a year of the first symptom report varied substantially by cardiologist from 0% in the lowest quartile to 100% in the highest (median, 29.6%; 25th–75th percentiles, 13.3%–47.0%). The distribution of AVR rates is provided in Figure S3 and by quartiles in Figure S4. Ranges for AVR rates by quartile were the following: quartile 1 (lowest treatment rates), 0 to 0.130; quartile 2, 0.133 to 0.294; quartile 3, 0.296 to 0.469; and quartile 4 (highest treatment rates), 0.470 to 1.000. Adjusted median AVR rates ranged from 13.6% in the lowest quartile to 57.2% in the highest quartile. Likewise, among patients who underwent AVR, substantial variation was observed in the use of TAVR, with 0% in the lowest quartile to 100% in the highest (median, 25%; 25th–75th percentiles, 0%–50%; adjusted median TAVR rates [lowest, highest], 32.7, 46.3%).

Factors Associated With AVR

Characteristics most strongly associated with no AVR within 1 year included age ≥80 years (adjusted HR for AVR, 0.56; 95% CI, 0.51–0.63) and dementia (adjusted HR, 0.32; 95% CI, 0.24–0.42). Among those treated, patient characteristics most strongly associated with TAVR (versus SAVR) included age ≥80 years (adjusted HR for TAVR, 20.8; 95% CI, 16.3–26.7) and prior percutaneous coronary intervention (adjusted HR, 2.27; 95% CI, 1.57–3.30). The full models are presented in
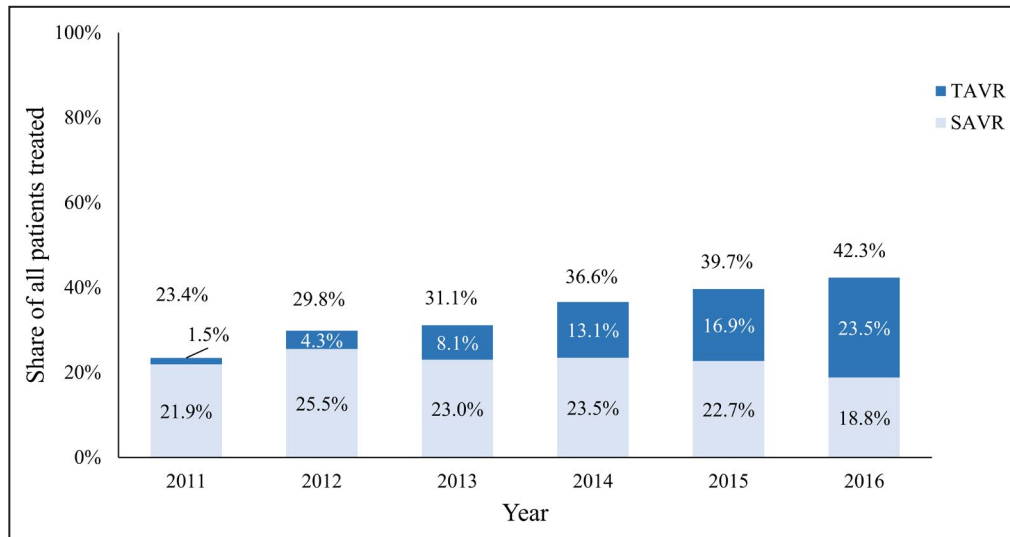
Figure 2. Treatment rates stratified by TAVR/SAVR over time.
Overall, 35.6% patients with symptomatic severe aortic stenosis (ssAS) had aortic valve replacement (n=9407) in the year after date of first ssAS diagnosis, whereas 37.3% of patients who had aortic valve replacement underwent TAVR (n=3513). SAVR indicates surgical aortic valve replacement; and TAVR, transcatheter aortic valve replacement.

Table S8. There was a significant correlation between the managing cardiologist's AVR rate and their rate of TAVR, with a Pearson correlation coefficient of 0.63 (P<0.001; Figure S5).

The managing cardiologist was among the strongest determinants of treatment for ssAS when compared with other covariates. Using the MOR, patients had a 125% and 141% increased chance of receiving a different treatment strategy if they had randomly selected a different managing cardiologist for AVR (MOR, 2.25; 95% CI, 2.14–2.36) and TAVR (MOR, 2.41; 95% CI, 2.21–2.61), respectively. Similarly, the median HR[27] was 1.265 (95% CI, 1.209–1.315; P<0.001), which demonstrates that the median increase in the hazard of mortality in the year after AVR was 26% when comparing a patient treated by a cardiologist with a lower referral rate with a patient treated by a cardiologist with a higher referral rate.

The strength of this association persisted over time and did not vary substantively by region (Table S9) or whether the managing cardiologist performed interventional procedures (adjusted MOR, 2.10; 95% CI, 1.89–2.31; non-cardiologist-adjusted MOR, 2.16; 95% CI, 2.04–2.28). By adjusting the model for volume of patients with ssAS and AVR volume, sensitivity analysis also showed the association persisted (Data S8). Treatment rates did vary substantively by the volume of patients with ssAS managed by the cardiologist (lowest tertile, highest tertile: 29.1%, 44.5%). Managing cardiologists with the highest volume of patients with ssAS by tertile had a slightly greater variation in AVR likelihood (adjusted MOR, 2.75; 95% CI, 2.37–3.12) compared with those with the lowest volume of patients with ssAS (adjusted MOR, 2.04; 95% CI, 1.89–2.19). A sensitivity analysis among a subset of patients with ejection fraction data showed that for patients with LVEF <50 (which is a Class I indication for AVR treatment), the MOR of AVR was 2.08 (95% CI, 1.87–2.28), similar to the MOR for the full model (2.25; 95% CI, 2.14–2.36). Further stratification showed similar results; the MOR of the likelihood of AVR was 2.03 (95% CI, 1.68–2.36) for LVEF <35, 2.01 (95% CI, 1.74–2.26) for LVEF 35–49, 2.18 (95% CI, 2.05–2.31) for LVEF ≥50, and 2.49 (95% CI, 2.30–2.69) for patients with LVEF "unknown," indicating that similar results are observed when the analysis is stratified by LVEF (MOR 95% CIs overlap for groups LVEF <35 [most severe] to LVEF ≥50 [less severe]; patients with unknown LVEF were most likely to undergo AVR).

Association Between the Managing Cardiologist's ssAS Treatment Variability and Patient Survival

The managing cardiologists' rates of AVR were directly associated with the likelihood of 1-year survival for their patients with ssAS (Figures 3 and 4). Patients managed by cardiologists in the highest quartile of treatment rates had a 1-year survival rate of 81% compared with 73% for the lowest quartile. After adjusting for differences in patient characteristics, patients with ssAS cared for by cardiologists in the lowest quartile of AVR rates experienced a higher associated risk of mortality than those treated by managing cardiologists
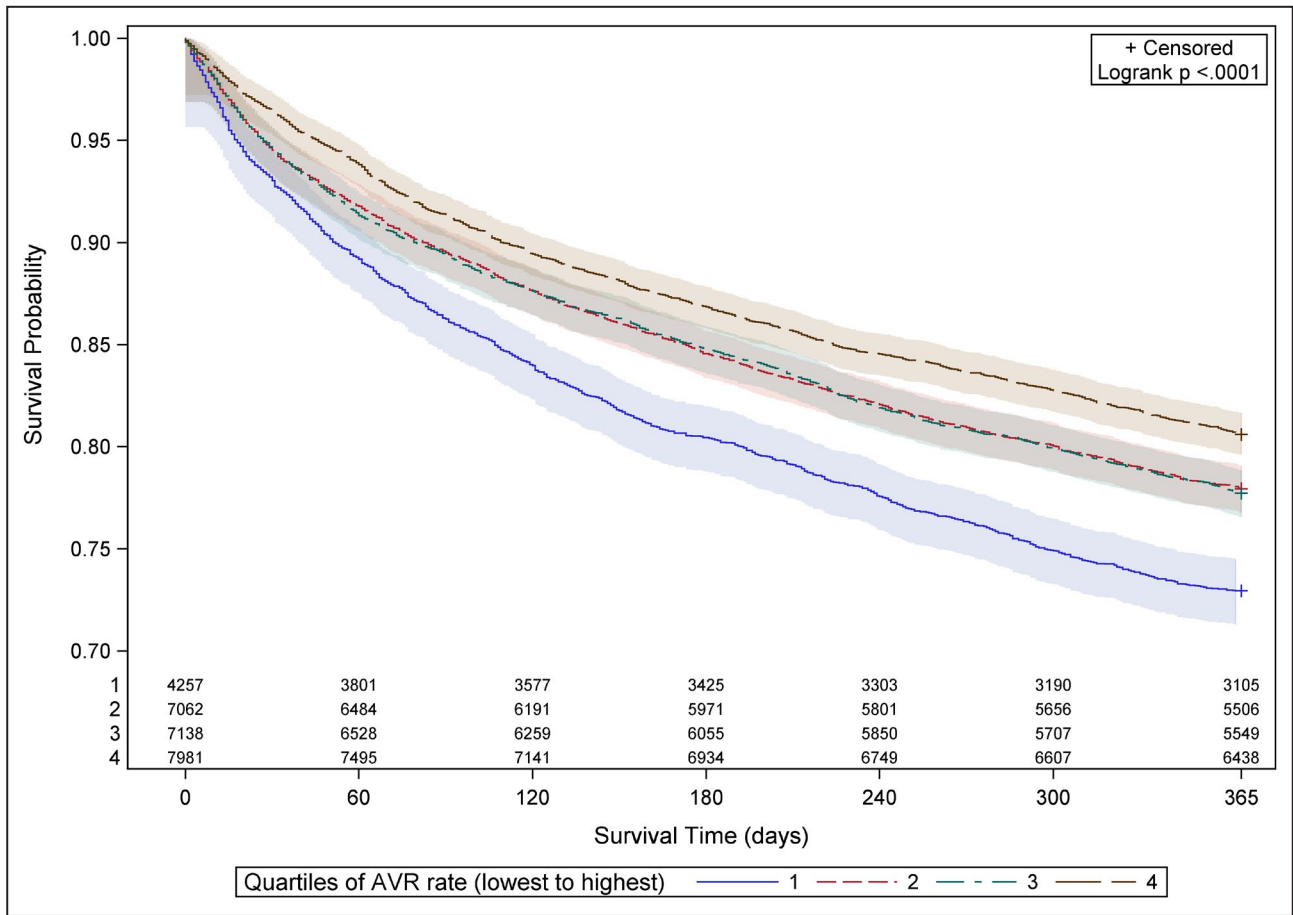
Figure 3. Survival stratified by managing cardiologist treatment rate.
Kaplan–Meier curves for survival when stratified by managing cardiologist AVR treatment rate with 1 representing the lowest quartile of AVR rates at the 1-year AVR rate and 4 the highest. Patients treated by cardiologists with higher AVR rates have a significantly higher survival at 1 year. The colored bands around each survival cure represent the 95% CI. The number of patients at risk at each 60-day interval for each quartile are displayed below the survival curves. AVR indicates aortic valve replacement.

in the highest quartile of AVR rates (adjusted HR, 1.22; 95% CI, 1.13–1.33). The following 2 sensitivity analyses were conducted to evaluate the impact on mortality: (1) an analysis to limit the impact of immortal time bias by limiting the window for AVR treatment to 3 months showed similar results (results found in Data S5 and Figures S6 and S7), and (2) an evaluation of the impact of cardiologists when removing physicians with >70% AVR treatment rates also revealed similar findings (see Data S6 for analysis results).

DISCUSSION

A substantial body of evidence documents the ability of AVR to prolong survival and alleviate suffering in patients with ssAS, resulting in the highest recommendation (Class 1A) for treating patients with ssAS with AVR in both US and European guidelines.[1,28] Despite widespread availability of this therapy, the majority of

patients with severe AS in our study did not undergo AVR within a year of symptom development. The current study is unique in that we identified patients with ssAS from a large database, evaluated the receipt of AVR within a year of ssAS diagnosis, and were able to describe an association between patient outcomes and the AVR rate of the managing cardiologist.

The percentage of patients treated with AVR in our study is similar to a previously published study by Lancellotti et al, which showed AVR treatment rates of 30% for patients with moderate AS and 45.1% for patients with severe AS upon study entry.[29] Nevertheless, these rates are not directly comparable with our results because the study by Lancellotti et al had longer follow-up time, excluded symptomatic patients with AS, and included non-US-based clinics.[29]

Across managing cardiologists, there was marked variability in a patient's likelihood for AVR, with the managing cardiologist among the strongest determinants of AVR. This variation was clinically important;
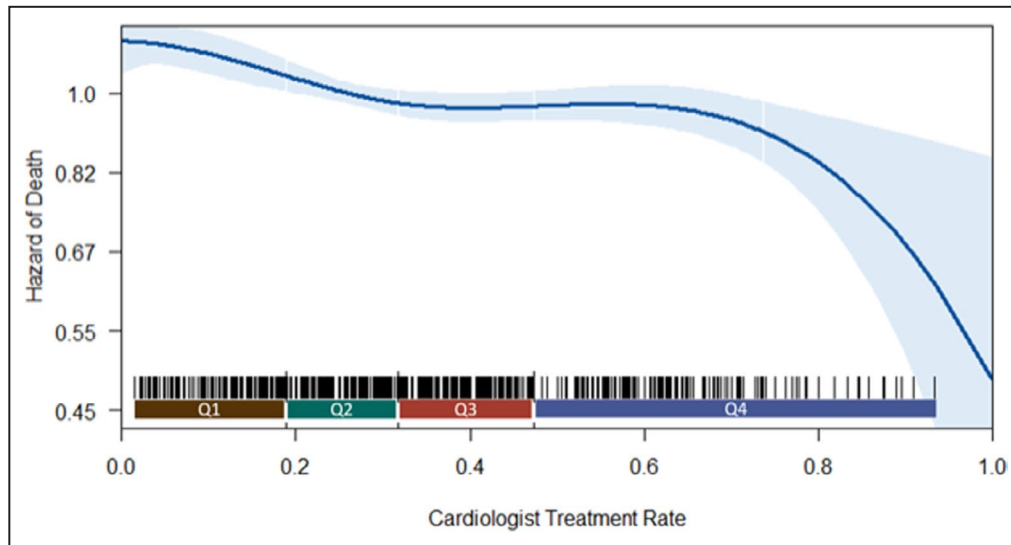
Figure 4. Association between the managing cardiologists' AVR treatment rate and 1-year all-cause mortality.
Association between managing cardiologists' 1-year AVR treatment rate and 1-year all-cause mortality was modeled as a restricted cubic spline with 4 degrees of freedom. The hazard presented was adjusted for patient factors and demographics and demonstrates that a higher clinician 1-year treatment rate is associated with a significantly reduced 1-year mortality risk. The distribution of clinicians by 1-year AVR rate is shown below the curve with each strike representing an individual clinician. The light blue band around the line represents the 95% CI. AVR indicates aortic valve replacement.

patients treated by cardiologists with low treatment rates had significantly lower 1-year survival compared with those treated by cardiologists with high treatment rates. Although more research is needed to determine what exactly drives the apparent variability in use of AVR by cardiologists, our findings show that there might potentially be issues in the current management of patients diagnosed with ssAS and that reducing variability in AVR treatment rates may present an opportunity for meaningful improvement.

The decision not to treat a patient with ssAS is complex, including anatomic considerations, comorbidities that affect the likelihood of therapeutic benefit, and a patient's individual values and preferences. A recent analysis of 407 patients with ssAS evaluated at 9 US heart valve treatment centers from 2013 to 2014 (including 17% who were ultimately medically managed) demonstrated a 31% rate of patient refusal.[30] Yet nearly one-third of these patients also expressed uncertainty with their ultimate treatment strategy; this uncertainty raises concerns as to whether patients were adequately educated as well as whether they were encouraged to be participants in a shared clinician–patient decision-making process. Nonetheless, considerations other than these affect the treatment options offered, including a patient's race and sex, as well as the local availability of treatment options.[31] As a result, patients who would be candidates for treatment may not be given the option.

Our analysis revealed that although there are some predictable factors (such as increased patient age and dementia) that were negatively associated with AVR (versus no AVR; age >80 years HR, 0.52 [95% CI, 0.45–0.61]; dementia HR, 0.33 [95% CI, 0.23–0.46]; Table S8), other factors, such as education and the Charlson Comorbidity Index (up through 3) were not found to be associated with AVR versus no AVR (education in 80th quantile HR, 0.90 [95% CI, 0.76–1.07]; Charlson Comorbidity Index 3 HR, 0.94 [95% CI, 0.79–1.11]; Table S8). Our study is consistent with other research that has shown a gradual decline in number of SAVR cases and a dramatic increase in number of TAVR cases in recent years.[32,33] Because TAVR is recommended for patients with comorbidities that would preclude them from referral for SAVR,[34] this may explain why our findings (our study used a definition of AVR that includes both TAVR and SAVR) showed no association between Charlson Comorbidity Index of 0 to 3 and AVR versus non-AVR. Of note, increasing Charlson comorbidity scores (2, 3, or 4+) were associated with an increased likelihood of TAVR versus SAVR (HR, 1.65–2.43, respectively; Table S8), corresponding with recommendations for the use of TAVR in higher risk individuals. The lack of association between income or education and propensity for AVR versus non-AVR may in part be attributed to insufficient granularity of the Optum database to accurately assess patient

socioeconomic status because it provides geographic information only at the zip-code level.

The use of a subjective surrogate (symptom report) for the recognition of clinically significant left ventricular strain may limit a more standardized application of AVR therapy. Of the individuals in our study, >90% presented with dyspnea (a nonspecific symptom that is notoriously difficult to elicit) as their primary clinical complaint. This finding is similar to other series[35–37] and raises concerns regarding the use of subjective clinical symptoms as the primary trigger for the treatment of this fatal disease. The low treatment rates of ssAS observed in this US cohort may speak to a broader challenge in symptom attribution for patients with ssAS. In an often debilitated, comorbid, and elderly population, symptoms of dyspnea can be difficult to elicit in a limited clinical visit.[7,38] When a more intensive search for symptoms has been undertaken, 3 separate studies have demonstrated that the vast majority (>80%) of patients with severe AS experience valve-associated symptoms.[18,39,40] Likewise, objective markers such as pro–B-type natriuretic peptide levels and 6-minute walk distance[41] have demonstrated left ventricular strain in large segments of patients who were otherwise asymptomatic. Clinical management guidelines have started a process of incorporating the use of these tests into their suggested treatment algorithms, and a more widespread use of objective metrics to trigger valve replacement for patients with ssAS may simplify clinical care, reduce treatment variability, and improve overall treatment rates in this terminal disease state.

Recognition of the scope of this possible performance gap is the first step to addressing the issue. Ensuring that AVR, a potentially life-saving treatment, is offered to all appropriate patients with ssAS in the United States will involve collaborative efforts throughout the valvular heart disease ecosystem. An educated patient is more likely to choose treatment, and patient education cannot rely solely on clinician-initiated programs. Although shared decision-making is critical in this preference-sensitive field, direct-to-patient educational programs from professional societies and patient advocacy groups may be helpful. Furthermore, both clinicians and health systems should examine their own practices to identify untreated patients and to implement systems that foster early recognition, active surveillance, and timely treatment of this terminal illness. With the availability of EHR analytics, new opportunities are emerging to take a more holistic, data-driven view of patient status. Finally, policy makers should continue working to reduce barriers to care by ensuring local access to treatment[42] and addressing the existing profit-margin differentials that have the potential to influence treatment decisions between TAVR and SAVR.

Limitations

This study has several notable limitations. First, the identification of severe AS for cohort development was based on a review of clinician notes rather than echocardiography reports. This approach may be subject to error, but it was subsequently validated through both evaluation of stratified survival curves and comparison to echocardiography reports in a subset of the cohort. Second, we were not able to validate symptom status in the Optum database, and although attempts were made to validate symptoms by evaluating treatment rates in the claims set, there were too few patients to conduct this analysis. Third, we used multivariate imputation by chained equations to impute missing variables with <10% of missing data and created an "unknown" category for variables in which data >10% were missing, which may have served a potential source of bias. Fourth, 90.4% of patients in our study had dyspnea, which is a subjective symptom. Therefore, we acknowledge that there is a possibility that patients not referred for AVR were dyspneic for reasons other than severe AS or that the dyspnea was mild in the judgment of the clinician. Fifth, the treatment rates observed here are among patients with an existing diagnosis of severe AS. Although the scope of the problem has not been well described, it is expected that a sizable cohort of patients never reach diagnosis, including among certain vulnerable populations.[43] As a result, the treatment rates observed here are likely an overestimate of actual treatment rates for this disease. Sixth, we identified managing cardiologists based on the frequency of interactions. This definition may not have accurately determined the "cardiology home" for some patients, particularly those with frequent hospitalizations; however, our results were consistent when applied to cardiologists in the outpatient setting. Seventh, we recognize that the decision to receive AVR involves a complex interaction between patient and clinician, as well as including patient values and preferences, neither of which could be evaluated in this study. Rates of patient refusal of AVR procedures are not recorded in the database and present a limitation; refusal rates are reported to be 20% to 33% (depending on race and other patient-related characteristics).[37] Eighth, in the survival benefit analysis, there is a risk of the immortal time bias since patients must survive long enough to undergo an AVR. A sensitivity analysis conducted using a shorter time window (3 months) from diagnosis to treatment revealed results similar to our primary analysis (1-year window). Ninth, we acknowledge the possibility that cardiologists with higher AVR treatment rates (referring more often) also worked with surgeons with good outcomes and that this may have contributed to potential confounding. Tenth, our analyses

were based on the assumption of random distribution of unmeasured confounding; however, similar to any observational analysis, this assumption may not hold and should be considered when interpreting the results. Finally, we acknowledge that the current study was conducted before the expansion of TAVR as an option for patients and that our results will need to be verified in future studies with more recent data.

CONCLUSIONS

In conclusion, a majority of patients in the United States with severe AS do not undergo AVR within a year of symptom development. We have identified substantial variation at the level of the managing cardiologist in the use of this therapy and an association between AVR treatment rates and 1-year survival of patients with ssAS. Given the availability of effective treatments, there may be value in implementing targeted initiatives to raise disease awareness, promote more objective diagnostic criteria, and reduce barriers to treatment.

ARTICLE INFORMATION

Affiliations

Duke Clinical Research Institute, Duke University School of Medicine, Durham, NC (J.M.B., A.L., S.V., T.Y.W., E.D.P.); Department of Family Medicine and Public Health, University of California, San Diego School of Medicine, San Diego, CA (P.S.); Boston Consulting Group, Boston, MA (P.S., I.J.B., O.L., S.G., J.J.); Department of Cardiovascular Surgery, Piedmont Heart Institute, Atlanta, GA (V.H.T.); and Columbia University Irving Medical Center and New York Presbyterian Hospital, , New York, NY (M.B.L.).

Acknowledgments

Sources of Funding

Disclosures

Dr Brennan reports consulting and speaking funds from Edwards Lifesciences and AtriCure. Dr Boero reports consulting for Edwards Lifesciences. Dr Thourani reports research and advising for Edwards Lifesciences. Dr Vemulapalli reports grants/contracts from the American College of Cardiology, Society of Thoracic Surgeons, Abbott Vascular, Boston Scientific, National Institutes of Health (R01 and Small Business Innovation Research grants), Food and Drug Administration National Evaluation System for health Technology Coordinating Center (FDA NESTcc), and Cytokinetics and advisory board/consulting/honoraria with Boston Scientific, American College of Physicians, Janssen, Edwards Lifesciences, and HeartFlow. Dr Wang reports research grants to the Duke Clinical Research Institute from Abbott, AstraZeneca, Bristol Myers Squibb, Boston Scientific, Cryolife, Chiesi, Merck, Portola, and Regeneron and consulting honoraria from AstraZeneca, Bristol Myers Squibb, Cryolife, and Novartis. Mr Liska, Mr Gander, and Mr Jager report consulting for Edwards Lifesciences. Dr Peterson reports being a coinvestigator on the American College of Cardiology Society of Thoracic Surgeons Transcatheter Valve Therapy TAVR Registry. The remaining authors have no disclosures to report.

Supplementary Material

Data S1–S8
Tables S1–S9
Figures S1–S7

REFERENCES

1. Nishimura RA, Otto CM, Bonow RO, Carabello BA, Erwin JP III, Fleisher LA, Jneid H, Mack MJ, McLeod CJ, O'Gara PT, et al. 2017 AHA/ACC focused update of the 2014 AHA/ACC guideline for the management of patients with valvular heart disease: a report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines. *Circulation*. 2017;135:e1159–e1195. DOI: 10.1161/CIR.0000000000000503.

2. Mack MJ, Leon MB, Smith CR, Miller DC, Moses JW, Tuzcu EM, Webb JG, Douglas PS, Anderson WN, Blackstone EH, et al.; PARTNER 1 Trial Investigators. 5-year outcomes of transcatheter aortic valve replacement or surgical aortic valve replacement for high surgical risk patients with aortic stenosis (PARTNER 1): a randomised controlled trial. *Lancet*. 2015;385:2477–2484. DOI: 10.1016/S0140-6736(15)60308-7.

3. Baron SJ, Arnold SV, Wang K, Magnuson EA, Chinnakondepali K, Makkar R, Herrmann HC, Kodali S, Thourani VH, Kapadia S, et al.; PARTNER 2 Investigators. Health status benefits of transcatheter vs surgical aortic valve replacement in patients with severe aortic stenosis at intermediate surgical risk: results from the PARTNER 2 randomized clinical trial. *JAMA Cardiol*. 2017;2:837–845. DOI: 10.1001/jamacardio.2017.2039.

4. ClinicalTrials.gov. PARTNER 3 trial: the safety and effectiveness of the SAPIEN 3 transcatheter heart valve in low risk patients with aortic stenosis (P3). ClinicalTrials.gov web site. Updated April 8, 2021. Available at: https://clinicaltrials.gov/ct2/show/NCT02675114. Accessed November 1, 2019.

5. ClinicalTrials.gov Medtronic evolut transcatheter aortic valve replacement in low risk patients. ClinicalTrials.gov web site. Available at: https://clinicaltrials.gov/ct2/show/NCT02701283. Updated October 30, 2019. Accessed November 1, 2019.

6. Dua A, Dang P, Shaker R, Varadarajan P, Pai RG. Barriers to surgery in severe aortic stenosis patients with Class I indications for aortic valve replacement. *J Heart Valve Dis*. 2011;20:396–400.

7. Bonow RO, Leon MB, Doshi D, Moat N. Management strategies and future challenges for aortic valve disease. *Lancet*. 2016;387:1312–1323. DOI: 10.1016/S0140-6736(16)00586-9.

8. Jones WS, Patel MR, Dai D, Subherwal S, Stafford J, Calhoun S, Peterson ED. Temporal trends and geographic variation of lower-extremity amputation in patients with peripheral artery disease: results from U.S. Medicare 2000–2008. *J Am Coll Cardiol*. 2012;60:2230–2236. DOI: 10.1016/j.jacc.2012.08.983.

9. Marzec LN, Peterson PN, Bao H, Curtis JP, Masoudi FA, Varosy PD, Bradley SM. Use of cardiac resynchronization therapy among eligible patients receiving an implantable cardioverter defibrillator: insights from the National Cardiovascular Data Registry Implantable Cardioverter Defibrillator Registry. *JAMA Cardiol*. 2017;2:561–565. DOI: 10.1001/jamacardio.2016.5388.

10. Messika-Zeitoun D, Verta P, Gregson J, Pocock SJ, Boero I, Feldman TE, Abraham WT, Lindenfeld J, Bax J, Leon M, et al. Impact of tricuspid regurgitation on survival in patients with heart failure: a large electronic health record patient-level database analysis. *Eur J Heart Fail*. 2020;22:1803–1813. DOI: 10.1002/ejhf.1830.

11. Matthew Brennan J, Leon MB, Sheridan P, Boero IJ, Chen Q, Lowenstern A, Thourani V, Vemulapalli S, Thomas K, Wang TY, et al. Racial differences in the use of aortic valve replacement for treatment of symptomatic severe aortic valve stenosis in the transcatheter aortic valve replacement era. *J Am Heart Assoc*. 2020;9:e015879. DOI: 10.1161/JAHA.119.015879.

12. Wallace PJ, Shah ND, Dennen T, Bleicher PA, Crown WH. Optum Labs: building a novel node in the learning health care system. *Health Aff (Millwood)*. 2014;33:1187–1194. DOI: 10.1377/hlthaff.2014.0038.

13. Halpern R, Seare J, Tong J, Hartry A, Olaoye A, Aigbogun MS. Using electronic health records to estimate the prevalence of agitation in Alzheimer disease/dementia. *Int J Geriatr Psychiatry*. 2019;34:420–431. DOI: 10.1002/gps.5030.

14. Nunes AP, Iglay K, Radican L, Engel SS, Yang J, Doherty MC, Dore DD. Hypoglycaemia seriousness and weight gain as determinants of cardiovascular disease outcomes among sulfonylurea users. *Diabetes Obes Metab*. 2017;19:1425–1435. DOI: 10.1111/dom.13000.

15. Nunes AP, Liang C, Gradishar WJ, Dalvi T, Lewis J, Jones N, Green E, Doherty M, Seeger JD. U.S. prevalence of endocrine therapy-naïve locally advanced or metastatic breast cancer. *Curr Oncol*. 2019;26:e180–e187. DOI: 10.3747/co.26.4163.

16. Loughlin AM, Lin N, Abler V, Carroll B. Tardive dyskinesia among patients using antipsychotic medications in customary clinical care in the United States. *PLoS One*. 2019;14:e0216044. DOI: 10.1371/journal.pone.0216044.

17. Bach DS, Siao D, Girard SE, Duvernoy C, McCallister BD, Gualano SK. Evaluation of patients with severe symptomatic aortic stenosis who do not undergo aortic valve replacement: the potential role of subjectively overestimated operative risk. *Circ Cardiovasc Qual Outcomes*. 2009;2:533–539. DOI: 10.1161/CIRCOUTCOMES.109.848259.

18. Campo J, Tsoris A, Kruse J, Karim A, Andrei AC, Liu M, Bonow RO, McCarthy P, Malaisrie SC. Prognosis of severe asymptomatic aortic stenosis with and without surgery. *Ann Thorac Surg*. 2019;108:74–79. DOI: 10.1016/j.athoracsur.2019.01.031.

19. Deyo RA, Cherkin DC, Ciol MA. Adapting a clinical comorbidity index for use with ICD-9-CM administrative databases. *J Clin Epidemiol*. 1992;45:613–619. DOI: 10.1016/0895-4356(92)90133-8.

20. Merchant RM, Berg RA, Yang L, Becker LB, Groeneveld PW, Chan PS; American Heart Association's Get With the Guidelines-Resuscitation Investigators. Hospital variation in survival after in-hospital cardiac arrest. *J Am Heart Assoc*. 2014;3:e000400. DOI: 10.1161/JAHA.113.000400.

21. Chan PS, Berg RA, Spertus JA, Schwamm LH, Bhatt DL, Fonarow GC, Heidenreich PA, Nallamothu BK, Tang F, Merchant RM; AHA GWTG-Resuscitation Investigators. Risk-standardizing survival for in-hospital cardiac arrest to facilitate hospital comparisons. *J Am Coll Cardiol*. 2013;62:601–609. DOI: 10.1016/j.jacc.2013.05.051.

22. Merlo J, Chaix B, Ohlsson H, Beckman A, Johnell K, Hjerpe P, Råstam L, Larsen K. A brief conceptual tutorial of multilevel analysis in social epidemiology: using measures of clustering in multilevel logistic regression to investigate contextual phenomena. *J Epidemiol Community Health*. 2006;60:290–297. DOI: 10.1136/jech.2004.029454.

23. Larsen K, Merlo J. Appropriate assessment of neighborhood effects on individual health: integrating random and fixed effects in multilevel logistic regression. *Am J Epidemiol*. 2005;161:81–88. DOI: 10.1093/aje/kwi017.

24. Larsen K, Petersen JH, Budtz-Jørgensen E, Endahl L. Interpreting parameters in the logistic regression model with random effects. *Biometrics*. 2004;56:909–914. DOI: 10.1111/j.0006-341X.2000.00909.x.

25. Hess KR. Assessing time-by-covariate interactions in proportional hazards regression models using cubic spline functions. *Stat Med*. 1994;13:1045–1062. DOI: 10.1002/sim.4780131007.

26. van Buuren S, Groothuis-Oudshoorn K. mice: multivariate imputation by chained equations in R. *J Stat Softw*. 2011;45:1–67.

27. Austin PC, Wagner P, Merlo J. The median hazard ratio: a useful measure of variance and general contextual effects in multilevel survival analysis. *Stat Med*. 2017;36:928–938. DOI: 10.1002/sim.7188.

28. Nishimura RA, Otto CM, Bonow RO, Carabellow BA, Erwin JP III, Guyton RA, O'Gara PT, Ruiz CE, Skubas NJ, Sorajja P, et al.; American College of Cardiology/American Heart Association Task Force on Practice Guidelines. 2014 AHA/ACC guideline for the management of patients with valvular heart disease: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines. *J Am Coll Cardiol*. 2014;63:e57–e185. DOI: 10.1016/j.jacc.2014.02.536.

29. Lancellotti P, Magne J, Dulgheru R, Clavel MA, Donal E, Vannan MA, Chambers J, Rosenhek R, Habib G, Lloyd G, et al. Outcomes of patients with asymptomatic aortic stenosis followed up in heart valve clinics. *JAMA Cardiol*. 2018;3:1060–1068. DOI: 10.1001/jamacardio.2018.3152.

30. Dharmarajan K, Foster J, Coylewright M, Green P, Vavalle JP, Faheem O, Huang P-H, Krishnaswamy A, Thourani VH, McCoy LA, et al. The medically managed patient with severe symptomatic aortic stenosis in the TAVR era: patient characteristics, reasons for medical management, and quality of shared decision making at heart valve treatment centers. *PLoS One*. 2017;12:e0175926. DOI: 10.1371/journal.pone.0175926.

31. Brennan JM, Bryant A, Boero I, Wang T, Vemulapalli S, Thourani V, Leon M, Peterson E. Race and sex-based disparities persist in the treatment of patients with severe, symptomatic aortic valve stenosis (Abstract number 1207). *J Am Coll Cardiol*. 2019;73(Suppl. 1):1207. DOI: 10.1016/S0735-1097(19)31814-5.

32. Kim KM, Shannon F, Paone G, Lall S, Batra S, Boeve T, DeLucia A, Patel HJ, Theurer PF, He C, et al. Evolving trends in aortic valve replacement: a statewide experience. *J Card Surg*. 2018;33:424–430. DOI: 10.1111/jocs.13740.

33. Badhwar V, Rankin JS, Thourani VH, D'Agostino RS, Habib RH, Shahian DM, Jacobs JP. The Society of Thoracic Surgeons adult cardiac surgery database: 2018 update on research: outcomes analysis, quality improvement, and patient safety. *Ann Thorac Surg*. 2018;106:8–13. DOI: 10.1016/j.athoracsur.2018.04.052.

34. Finn M, Green P. Transcatheter aortic valve implantation in the elderly: who to refer? *Prog Cardiovasc Dis*. 2014;57:215–225. DOI: 10.1016/j.pcad.2014.08.003.

35. Martínez-Sellés M, Gómez Doblas JJ, Carro Hevia A, García de la Villa B, Ferreira-González I, Alonso Tello A, Andión Ogando R, Ripoll Vera T, Arribas Jiménez A, Carrillo P, et al.; PEGASO Registry Group. Prospective registry of symptomatic severe aortic stenosis in octogenarians: a need for intervention. *J Intern Med*. 2014;275:608–620. DOI: 10.1111/joim.12174.

36. Hartzell M, Malhotra R, Yared K, Rosenfield HR, Walker JD, Wood MJ. Effect of gender on treatment and outcomes in severe aortic stenosis. *Am J Cardiol*. 2011;107:1681–1686. DOI: 10.1016/j.amjcard.2011.01.059.

37. Yeung M, Kerrigan J, Sodhi S, Huang PH, Novak E, Maniar H, Zajarias A. Racial differences in rates of aortic valve replacement in patients with severe aortic stenosis. *Am J Cardiol*. 2013;112:991–995. DOI: 10.1016/j.amjcard.2013.05.030.

38. Taniguchi T, Morimoto T, Shiomi H, Ando K, Kanamori N, Murata K, Kitai T, Kawase Y, Izumi C, Miyake M, et al.; CURRENT AS Registry Investigators. Initial surgical versus conservative strategies in patients with asymptomatic severe aortic stenosis. *J Am Coll Cardiol*. 2015;66:2827–2838. DOI: 10.1016/j.jacc.2015.10.001.

39. Attias D, Macron L, Dreyfus J, Monin JL, Brochet E, Lepage L, Hekimian G, Lung B, Vahanian A, Messika-Zeitoun D. Relationship between longitudinal strain and symptomatic status in aortic stenosis. *J Am Soc Echocardiogr*. 2013;26:868–874. DOI: 10.1016/j.echo.2013.05.004.

40. Goliasch G, Kammerlander AA, Nitsche C, Dona C, Schachner L, Öztürk B, Binder C, Duca F, Aschauer S, Laufer G, et al. Syncope: the underestimated threat in severe aortic stenosis. *JACC Cardiovasc Imaging*. 2019;12:225–232. DOI: 10.1016/j.jcmg.2018.09.020.

41. Redfors B, Pibarot P, Gillam LD, Burkhoff D, Bax JJ, Lindman BR, Bonow RO, O'Gara PT, Leon MB, Généreux P. Stress testing in asymptomatic aortic stenosis. *Circulation*. 2017;135:1956–1976. DOI: 10.1161/CIRCULATIONAHA.116.025457.

42. Vora AN, Vemulapalli S. Geographic dispersion of TAVR services: ensuring availability while maintaining quality. *Am Heart J*. 2016;177:160–162. DOI: 10.1016/j.ahj.2016.04.005.

43. Beydoun HA, Beydoun MA, Liang H, Dore GA, Shaked D, Zonderman AB, Eid SM. Sex, race, and socioeconomic disparities in patients with aortic stenosis (from a nationwide inpatient sample). *Am J Cardiol*. 2016;118:860–865. DOI: 10.1016/j.amjcard.2016.06.039.

SUPPLEMENTAL MATERIAL

Supplemental Methods

Data S1. Validation of Optum physician report of aortic stenosis

To validate Optum physician's report of aortic stenosis, we leveraged the following approach:

- Among 26,438 patients with symptomatic severe aortic stenosis (ssAS) in the final cohort, we pulled the closest echocardiography readings to severe aortic stenosis (sAS) diagnosis identified by physicians' notes
  - Echocardiography readings included aortic valve area (AVA), velocity, mean gradient, and left ventricular ejection fraction (LVEF)
  - The closest echocardiography readings in the seven days before sAS diagnosis from physicians' notes were pulled. The LVEF is included only if it is on the same day of AVA/velocity/mean gradient. The completeness of echocardiography readings is shown in **Table S1**

  - We restricted patients to those with each of three (AVA, velocity, and mean gradient) available measurements and to those who with four (AVA, velocity, mean gradient and LVEF) measurements available. We then compared the difference in sAS diagnoses using physician's notes to the severity using AS definitions from the 3 or 4 echocardiography parameters. The differences are listed as below.
    - American Heart Association (AHA) guidelines were applied here to define the severity of AS by using AVA, velocity, or mean gradient
    - Echocardiography readings were categorized as mild, moderate or severe based on the 3, or 4, echocardiography parameters and agreement with patients identified as having severe AS with physicians' notes are compared (see **Table S2**)

  - The severity of AS by echocardiography readings stratified by LVEF level is shown in **Table S3**.

  - The severity of AS by echocardiography readings stratified by left ventricular outflow tract velocity time integral (LVOT VTI) level is shown in **Table S4**.

Data S2. Sensitivity analysis of the core analysis focusing only on outpatient managing cardiologists

Similar trends were observed when restricting to patients with managing cardiologist classification based on outpatient visits only (n=23,013). In the subset of patients treated by these cardiologists, 36.1% of ssAS patients underwent AVR (13.8% TAVR, 22.3% SAVR). Rates of AVR within a year of diagnosis varied substantially by cardiologist, from 0% in the lowest quartile of treatment rates to 100% in the highest (median 30.0%, 25th–75th 16.7–47.4%). Among outpatient cardiologists, the association between the managing cardiologist and the odds of an alternative treatment strategy was similar to that observed in the overall cohort (adjusted MOR 2.21, 95% CI 2.10–2.33).

Data S3. Sensitivity analysis by using a claims-linked cohort.

1. To internally validate our results, we repeated the core analyses in Optum's claims-linked patient set. The integrated patient set includes a substantially smaller subset of patients within the EHR who can also be linked to insurance claims via a distinct patient ID. Linkage to insurance claims allows for assessing to lower rates of missing data. After applying our inclusion and exclusion criteria to this cohort, a subset of 926 patients managed by 172 cardiologists were identified.
2. There are 33.4% of ssAS patients (n = 301) undergoing AVR in the first year after diagnosis. The median time between date of ssAS diagnosis and AVR was 48 days (25th-75th percentiles:18-89 days), which stayed consistent compared to major analysis.
3. Rates of AVR within a year of the first ssAS diagnosis varied significantly by cardiologist from 1% in the lowest quartile of AVR rates to 100% in the highest (median 33.3%, 25th-75th percentiles 3.8-50%).
4. Patients had a 135% chance of receiving a different AVR treatment plan if they had seen a random managing cardiologist for AVR (MOR 2.35, 95% CI 1.72-2.94), which was similar to the pattern in the major set.

Data S4. Subset analysis with lab data available.

A complete case analysis was performed including only patients with available data for ejection fraction, creatinine, and body mass index to evaluate the potential impact of missing data for these variables on the risk-adjusted results.

1. Full multi-level logistic models for the likelihood of AVR (vs. no AVR) and the likelihood of TAVR (vs. SAVR), expressed a Median Odds Ratios (MOR) were conducted. The models included patient-level and clinician-level factors among patients with available values for ejection fraction, creatinine, and body mass index (**Table S8**). The clinician was one of the strongest determinants of ssAS. Similar patterns were observed when we restricted patients to those with available values for ejection fraction, creatinine, and body mass index.

2. Median odds rations (MOR) for general cardiologists for the likelihood of AVR when stratified by region and time is shown below. The results stayed consistent compared to those in the main analysis (see **Table S9**).

    Similar trends were observed when restricting to patients with managing cardiologist classification based only on outpatient visits among complete sub-data set. The association between the managing cardiologist and the odds of an alternative treatment strategy was similar to that observed in the overall cohort (adjusted MOR 2.10, 95% CI 1.97-2.23).

3. Association between clinician 1-year treatment rate and 1-year all-cause mortality with clinician 1-year treatment rate was modeled as a restricted cubic spline with 4 degrees of freedom (See **Figure S2**). The hazard presented was adjusted for patient factors and demographics and demonstrates that a higher clinician 1-year treatment rate is associated with a significantly reduced 1-year mortality risk. The distribution of cardiologists by 1-year AVR rate is shown below the curve with each strike representing an individual clinician. The analysis is based on patients with the available values for ejection fraction, creatinine, and body mass index.

Data S5. Clinician 3-month AVR rate and 1-year all-cause mortality to evaluate the impact of immortal time bias.

In order to limit the impact of immortal time bias, we shortened the window from ssAS diagnosis to AVR treatment to 3-months.

1. Association between clinician managing cardiologists' 3-month AVR treatment rate and 1-year all-cause mortality with clinician 3-month treatment rate was modeled as a restricted cubic spline with 4 degrees of freedom **(Figure S3).** The hazard presented was adjusted for patient factors and demographics and demonstrates that a higher clinician 3-month treatment rate is associated with a significantly reduced 1-year mortality risk. The distribution of cardiologists by 3-month AVR rate is shown below the curve with each strike representing an individual clinician.

2. *Survival stratified by managing cardiologist 3-month treatment rate.* Kaplan Meier curves for survival when stratified by managing cardiologist AVR treatment rate within a 3-month period (1 represents the lowest quartile of AVR rates, and 4 the highest) **(Figure S4).** Patients managed by cardiologists with higher AVR rates have a significantly higher survival at one year.

3. After adjusting for differences in patient characteristics, ssAS patients cared for by cardiologists in the lowest quartile of 3-month AVR rates experienced a higher associated risk of mortality than those treated by managing cardiologists in the highest quartile of 3-month AVR rates (adjusted HR 1.11, 95% CI 1.02–1.21). The results stayed consistent compared to that in the primary cohort.

Data S6. Sensitivity analysis: Restricting cohort to patients treated by cardiologists with AVR rates ≤ 70%

To evaluate the relative impact of cardiologists with high AVR rates on patient mortality, a sensitivity analysis was conducted by removing patients treated by cardiologists with AVR intervention rates greater than 70%. The resulting median odds ratio (MOR) was 1.99 (95% CI: 1.90-2.08). While this value is somewhat lower compared to the full patient cohort (including patients treated by cardiologists with comprehensive AVR treatment rates) (MOR 2.25, 95% CI: 2.14–2.36), restricting the cohort to cardiologists with AVR rates ≤ 70% did not significantly impact our findings.

Data S7. Details on multiple imputation.

Imputation replaced 9%, 6%, 3%, 3%, 0.2%, and 0.2% of missing data for insurance, smoking, income, education, gender, and age, respectively; this rate of missing data is within previously reported ranges.[20] Missing data for variables with more than 10% missing, including left ventricular ejection fraction (LVEF) (31%), creatinine (20%), and body mass index (11%) were coded as "unknown."

Data S8. Sensitivity analysis: Adding the cardiologist case-load (both ssAS patients and AVR volume) to the main model.

To evaluate the impact of cardiologist case load, we conducted a sensitivity analyses by adding both ssAS patient volume and AVR volume to the main model. The median odds ratio of AVR for this model was 1.677 (95% CI 1.614-1.739), P<0.001, after adjustment for ssAS and AVR volume (tertiles). Although the MOR for AVR was lower compared to the model without case-load (MOR 2.25, 95% CI: 2.14–2.36), the results were still significant.
Of note, the OR of AVR for provider ssAS volume (highest tertile vs. lowest tertile) 0.175 (0.147-0.210) P<0.001; OR of AVR for provider AVR volume (highest tertile vs lowest tertile) 27.123 (22.242-33.073) P<0.001.

Table S1. Completeness of echocardiography readings.

Patients with available specific echocardiography readings	Completeness of data
AVA	8,032 (30.4%)
Velocity	3,323 (12.6%)
Mean gradient	8,233 (31.1%)
LVEF	9,464 (35.8%)
AVA + Velocity	1,490 (5.6%)
AVA + Velocity + Mean gradient	1,206 (4.6%)
AVA + Velocity + Mean gradient + LVEF	1,057 (4.0%)

Table S2. Echocardiography readings identified as severe AS.

Classification by echocardiography Tests	Classification as severe by physicians' notes	
	Patients with all available echocardiography readings for AVA, velocity, and mean gradient	Patients with all available echocardiography readings for AVA, velocity, mean gradient, and LVEF
Mild AS	17 (1.4%)	12 (1.1%)
Moderate AS	259 (21.5%)	192 (18.2%)
Severe AS	930 (7.1%)	853 (0.7%)

Table S3. Severity of AS by echocardiography readings stratified by LVEF.

Level of LVEF	Classification by Echocardiography Tests (among patients with severe AS by clinician notes)		
	Mild AS	Moderate AS	Severe AS
< 30%	0 (0.0%)	19 (1.8%)	63 (6.0%)
30% - 49%	3 (0.28%)	26 (2.5%)	139 (13.2%)
≥ 50%	9 (0.85%)	147 (13.9%)	651 (61.6%)
Patients with all available echocardiography readings for AVA velocity, mean gradient, and LVEF. Data listed as n (% of whole)			

Table S4. Severity of AS by echocardiography readings stratified by left ventricular outflow tract velocity time integral (LVOT VTI) level.

Level of LVOT VTI	Classification by echocardiography Tests		
	Mild AS	Moderate AS	Severe AS
< 18	5 (100.0%)	9 (20.9%)	61 (26.1%)
18 - 22	0 (0.0%)	11 (25.6%)	60 (26.5%)
> 22	0 (0.0%)	23 (53.5%)	109 (47.4%)
Patients with all available echocardiography readings for AVA, velocity, mean gradient, and LVEF. Data listed as n (% of column total).			

Table S5. ICD-9-CM and ICD-10-CM procedure and diagnostic codes, and CPT codes.

	ICD-9-CM	ICD-10-CM	CPT
Atrial fibrillation	42731	I480-I484, I489, I4891-I4892	
Cancer	140-172, 174-194, 196-198, 1990-1991, 200-208, 1950-1958	C0-C1, C20-C26, C30-C34, C37-C41, C43, C45-C58, C60-C85, C88, C90-C97	
Cardiac conduction disorders	4260, 4261, 42611, 42612, 42613, 4262, 4263, 4264, 42650, 42651, 42652, 42653, 42654, 4266	I440, I441, I442, I443, I4430, I4439, I450, I451, I4510, I4519, I452, I444, I445, I446, I4460, I4469, I447, I453	
COPD	49, 500, 501, 502, 503, 504, 505	I278, I279, J684, J701, J703, J40, J41, J42, J43, J44, J45, J46, J47, J60, J61, J62, J63, J64, J65, J66, J67	
Dementia	290	F051, G311, F00, F01, F02, F03, G30	
Diabetes without complications	2500, 2501, 2502, 2503, 2507	E100, E101, E106, E108, E109, E110, E111, E116, E118, E119, E120, E121, E126, E128, E129, E130, E131, E136, E138, E139, E140, E141, E146, E148, E149	
Diabetes with complications	2504, 2505, 2506	E102, E103, E104, E105, E107, E112, E113, E114, E115, E117, E122, E123, E124, E125, E127, E132, E133, E134, E135, E137, E142, E143, E144, E145, E147	
Prior myocardial infarction	410, 412	I21, I22, I252	
Osteoarthritis (OA)	715	M15-M19	
Peripheral vascular disease (PVD)	4439, 441, 7854, V434	I731, I738, I739, I771, I790, I792, K551, K558, K559, Z958, Z959, I70, I71	
Heart failure (SDS terms)	4282, 42820, 42821, 42822, 42823, 4283, 42830, 42831, 42832, 42833, 4284, 42840, 42841, 42842, 42843	I502, I5020, I5021, I5022, I5023, I503, I5030, I5031, I5032, I504, I5040, I5041, I5042, I5043	
Moderate to severe renal disease	582, 5830, 5831, 5832, 5833, 5834, 5835, 5836, 5837, 585, 586, 588	I120, I131, N032, N033, N034, N035, N036, N037, N052, N053, N054, N055, N056, N057, N250, Z490, Z491, Z492, Z940, Z992, N18, N19	
Supplemental oxygen use	V462	Z9981	E1390, E1391, E0424, E0439, E1405, E1406, E0431, E0434, E1392, E0433, K0738, E0441, E0442, E0443, E0444, E0425, E0430, E0431,

			E0433, E0434, E0435, E0440, E0445, E0446
Percutaneous cardiac procedures (including PCI, ablation, and transcatheter mitral)	00.66, 36.06, 36.07, 37.26, 37.27, 37.33, 37.34, 35.97	270346, 027034Z, 02703D6, 02703DZ, 270446, 027044Z, 02704D6, 02704DZ, 271346, 027134Z, 02713D6, 02713DZ, 271446, 027144Z, 02714D6, 02714DZ, 272346, 027234Z, 02723D6, 02723DZ, 272446, 027244Z, 02724D6, 02724DZ, 273346, 027334Z, 02733D6, 02733DZ, 273446, 027344Z, 02734D6, 02734DZ, 02563ZZ, 02573ZZ, 025K3ZZ, 025L3ZZ, 02B63ZZ, 02B73ZZ, 02BK3ZZ, 02BL3ZZ, 02560ZZ, 02570ZZ, 025K0ZZ, 025L0ZZ, 02B60ZZ, 02B70ZZ, 02BK0ZZ, 02BL0ZZ, 02T80ZZ, 02K80ZZ, 02K83ZZ, 02K84ZZ, 4A023FZ, 02UG3JZ	92937, 92941, 92943, 92920, 92924, 92928, 92933, 33418, 33419
Pacemaker/ICD	00.51, 00.54, 37.94, 37.95, 37.96, 37.80, 37.81, 37.82, 37.83	02HK0KZ, 02HK3KZ, 02HK4KZ, 02HL0KZ, 02HL3KZ, 02HL4KZ, 0JH609Z, 0JH639Z, 0JH809Z, 0JH839Z, 0JH609Z, 0JH609Z, 0JH639Z, 0JH639Z, 0JH809Z, 0JH839Z, 0JPT0PZ, 0JPT3PZ, 02H60KZ, 02H60KZ, 02H63KZ, 02H63KZ, 02H64KZ, 02H64KZ, 02H70KZ, 02H70KZ, 02H73KZ, 02H73KZ, 02H74KZ, 02H74KZ, 02HK0KZ, 02HK0KZ, 02HK3KZ, 02HK3KZ, 02HK4KZ, 02HK4KZ, 02HL0KZ, 02HL0KZ, 02HL3KZ, 02HL3KZ, 02HL4KZ, 02HL4KZ, 02PA0MZ, 02PA3MZ, 02PA4MZ, 02PAXMZ, 0JH608Z, 0JH608Z, 0JH638Z, 0JH638Z, 0JH808Z, 0JH808Z, 0JH838Z, 0JH838Z, 0JPT0PZ, 0JPT3PZ, 02H63KZ, 02H73KZ, 02HK3KZ, 02HL3KZ, 02HN0KZ, 02HN4KZ, 0JH608Z, 0JH638Z, 0JH808Z, 0JH838Z, 0JH60PZ, 0JH60PZ, 0JH63PZ, 0JH63PZ, 0JH80PZ, 0JH80PZ, 0JH83PZ, 0JH83PZ, 0JPT0PZ, 0JPT3PZ, 0JH604Z, 0JH634Z, 0JH804Z, 0JH834Z, 0JH605Z, 0JH635Z, 0JH805Z, 0JH835Z, 0JH606Z, 0JH636Z, 0JH806Z, 0JH836Z	33202, 33203, 33216, 33217, 33224, 33230, 33231, 33240, 33249, 33270, 33271, 33202, 33203, 33206, 33207, 33208, 33212, 33213, 33221, 33216, 33217, 33224
Hemodialysis	39.95, 54.98	5A1D00Z, 5A1D00Z, 3E1M39Z	90935, 90937, 90945, 90947, 4055F

AVR	35.05, 35.06, 35.21, 35.22	02RFxxx	3405-6, 33410-13; 33361-33366, 0265T, 0257T, 0318T
TAVR	35.05, 35.06	02RF37Z, 02RF38Z, 02RF3JZ, X2RF332, 02RF3KZ, 02RF37H, 02RF38H, 02RF3JH, 02RF3KH	0265T, 0257T, 0318T, 33361-33366

COPD, chronic obstructive pulmonary disease; CPT, Current Procedural Terminology; ICD, implantable cardioverter defibrillator; ICD-9-CM, International Classification of Diseases, Ninth Revision, Clinical Modification; ICD-10-CM, International Classification of Diseases, Tenth Revision, Clinical Modification; PCI, percutaneous coronary intervention; SDS, signs, diseases, and symptoms

Table S6. Full, multi-level, logistic models for the likelihood of AVR (vs. no AVR) and the likelihood of TAVR (vs. SAVR) in patients with lab data.

Patient Characteristics	AVR vs non-AVR		TAVR vs SAVR	
	HR (95% CI)	P-value	HR (95% CI)	P-value
Gender				
Male	Reference		Reference	
Female	0.75 (0.71, 0.80)	<.0001	1.46 (1.28, 1.65)	<.0001
Age				
<65	Reference		Reference	
65-79	1.05 (0.95, 1.16)	0.1940	3.90 (3.07, 4.93)	<.0001
80+	0.56 (0.51, 0.63)	<.0001	20.83 (16.25, 26.69)	<.0001
Race				
Non-Hispanic white	Reference		Reference	
Non-Hispanic black	0.69 (0.58, 0.83)	0.0001	1.06 (0.73, 1.53)	0.7746
Asian	0.97 (0.63, 1.49)	0.8842	1.12 (0.52, 2.40)	0.7748
Hispanic	0.91 (0.75, 1.10)	0.3158	0.69 (0.47, 1.03)	0.0630
Other/unknown	0.79 (0.68, 0.93)	0.0036	1.03 (0.74, 1.43)	0.8624
Division				
East North Central	Reference		Reference	
East South Central	2.20 (1.73, 2.81)	<.0001	1.33 (0.92, 1.92)	0.1286
Middle Atlantic	1.33 (1.07, 1.66)	0.0105	1.87 (1.33, 2.64)	0.0003
Mountain	1.95 (1.49, 2.55)	<.0001	0.51 (0.33, 0.79)	0.0025
New England	0.82 (0.62, 1.09)	0.1715	1.91 (1.16, 3.15)	0.0109
Pacific	1.18 (0.94, 1.48)	0.1537	1.31 (0.90, 1.89)	0.1594
South Atlantic/West South Central	1.30 (1.10, 1.53)	0.0020	1.55 (1.17, 2.03)	0.0019
West North Central	1.26 (1.09, 1.46)	0.0018	0.75 (0.58, 0.96)	0.0236
Other/unknown	1.11 (0.89, 1.38)	0.3505	0.96 (0.62, 1.49)	0.8472
Income level (quantiles)				
<20th	Reference		Reference	
20th-40th	1.00 (0.88, 1.14)	0.9908	0.96 (0.75, 1.23)	0.7440
40th-60th	1.04 (0.92, 1.18)	0.5315	1.14 (0.91, 1.43)	0.2437
60th-80th	1.03 (0.91, 1.17)	0.6700	1.15 (0.91, 1.46)	0.2459
80th+	1.07 (0.92, 1.24)	0.3681	1.12 (0.85, 1.47)	0.4133
Education level (quantiles)				
<20th	Reference		Reference	
20th-40th	1.04 (0.91, 1.18)	0.5667	0.85 (0.67, 1.09)	0.1979
40th-60th	0.85 (0.76, 0.96)	0.0066	0.83 (0.66, 1.03)	0.0838
60th-80th	0.90 (0.80, 1.02)	0.0935	0.84 (0.68, 1.05)	0.1283

80th+	0.84 (0.74, 0.96)	0.0102	1.01 (0.79, 1.30)	0.9353
Insurance				
Medicare	Reference		Reference	
Commercial	1.20 (1.09, 1.31)	0.0002	0.77 (0.64, 0.93)	0.0067
Medicaid	0.93 (0.76, 1.13)	0.4601	1.10 (0.71, 1.72)	0.6588
Uninsured	1.09 (0.87, 1.38)	0.4591	0.93 (0.59, 1.48)	0.7720
Other or Unknown	1.21 (1.12, 1.32)	<.0001	0.89 (0.76, 1.04)	0.1328
Charlson Comorbidity Index				
0	Reference		Reference	
1	1.03 (0.94, 1.12)	0.5566	1.26 (1.06, 1.51)	0.0101
2	0.98 (0.88, 1.09)	0.6881	1.56 (1.25, 1.94)	<.0001
3	0.96 (0.84, 1.09)	0.5245	1.97 (1.51, 2.57)	<.0001
4+	0.82 (0.69, 0.97)	0.0194	2.71 (1.93, 3.80)	<.0001
Atrial fibrillation	0.75 (0.70, 0.81)	<.0001	1.07 (0.93, 1.24)	0.3271
Cancer	0.90 (0.81, 1.01)	0.0666	0.85 (0.68, 1.06)	0.1438
Conduction	0.92 (0.83, 1.03)	0.1488	1.07 (0.87, 1.32)	0.5020
COPD	0.80 (0.71, 0.9)	0.0001	1.46 (1.16, 1.83)	0.0011
Dementia	0.32 (0.24, 0.42)	<.0001	1.82 (0.88, 3.75)	0.1068
Diabetes with complications	1.01 (0.87, 1.16)	0.9316	0.77 (0.59, 1.01)	0.0625
Diabetes without complications	1.06 (0.98, 1.15)	0.1256	1.01 (0.86, 1.17)	0.9480
Prior myocardial infarction	1.00 (0.90, 1.12)	0.9673	1.03 (0.83, 1.28)	0.7939
Osteoarthritis	0.94 (0.86, 1.03)	0.2087	0.99 (0.84, 1.18)	0.9384
Peripheral vascular disease	0.98 (0.89, 1.07)	0.5856	0.93 (0.78, 1.11)	0.4230
Heart failure	0.99 (0.90, 1.08)	0.8336	1.33 (1.12, 1.58)	0.0012
Moderate to severe renal disease	0.92 (0.82, 1.03)	0.1645	0.89 (0.71, 1.12)	0.3158
Smoking status				
Previous	Reference		Reference	
Current	1.05 (0.95, 1.16)	0.3217	0.80 (0.66, 0.98)	0.0324
Never	1.02 (0.95, 1.09)	0.6307	0.88 (0.77, 1.00)	0.0536
Use of supplemental oxygen	0.62 (0.52, 0.74)	<.0001	2.96 (2.00, 4.38)	<.0001
Percutaneous coronary intervention	1.09 (0.90, 1.32)	0.3945	2.27 (1.57, 3.30)	<.0001
Pacemaker	0.96 (0.72, 1.27)	0.7686	1.36 (0.74, 2.50)	0.3245
Hemodialysis	0.84 (0.61, 1.17)	0.3048	0.85 (0.39, 1.84)	0.6715
Dyspnea	1.65 (1.48, 1.84)	<.0001	1.24 (0.98, 1.58)	0.0759
Dyspnea on exertion	1.51 (1.39, 1.65)	<.0001	1.03 (0.88, 1.21)	0.7188
Angina	1.13 (1.06, 1.21)	0.0004	0.95 (0.84, 1.09)	0.4752
Syncope	0.94 (0.88, 1.01)	0.0724	1.09 (0.96, 1.25)	0.1863
Ejection fraction				
50+	Reference		Reference	

<34	0.61 (0.54, 0.69)	<.0001	1.50 (1.16, 1.95)	0.0021
35-49	0.79 (0.71, 0.88)	<.0001	1.44 (1.18, 1.77)	0.0004
Creatinine				
<0.9	Reference			
1.0-1.4	0.93 (0.86, 1.00)	0.0590	Reference	
1.5-1.9	0.69 (0.61, 0.79)	<.0001	2.01 (1.57, 2.59)	<.0001
2.0+	0.48 (0.41, 0.57)	<.0001	2.72 (1.93, 3.83)	<.0001
BMI				
20.1-25.0	Reference		Reference	
<20.0	0.71 (0.59, 0.84)	<.0001	2.11 (1.41, 3.15)	0.0003
25.1-30.0	1.34 (1.24, 1.46)	<.0001	0.87 (0.74, 1.04)	0.1237
30.1+	1.54 (1.41, 1.68)	<.0001	0.94 (0.79, 1.11)	0.4553
Year of diagnosis				
2011	Reference		Reference	
2012	1.55 (1.35, 1.77)	<.0001	2.88 (1.87, 4.43)	<.0001
2013	1.71 (1.50, 1.95)	<.0001	6.51 (4.33, 9.79)	<.0001
2014	2.17 (1.91, 2.47)	<.0001	10.60 (7.08, 15.88)	<.0001
2015	2.52 (2.22, 2.86)	<.0001	15.58 (10.45, 23.25)	<.0001
2016	3.03 (2.66, 3.45)	<.0001	27.96 (18.66, 41.9)	<.0001
Diagnosed in inpatient	0.67 (0.61, 0.73)	<.0001	1.18 (1.00, 1.39)	0.0541
Hospitalized in year prior	0.75 (0.68, 0.81)	<.0001	0.89 (0.75, 1.06)	0.2028
Median odds ratio for cardiologist	2.25 (2.14, 2.36)	<.0001	2.41 (2.21, 2.61)	<.0001

AVR, aortic valve replacement; BMI, body mass index; CI, confidence interval; COPD, chronic obstructive pulmonary disease; HR, hazard ratio; MOR, median odds ratio; SAVR, surgical aortic valve replacement; ssAS, symptomatic severe aortic stenosis; TAVR, transcatheter aortic valve replacement

Table S7. Median odds ratios (MOR) for managing cardiologists for the likelihood of AVR when stratified by region and time in patients with lab data.

Stratification	MOR for AVR (95% CI)
	All patients
Region	
New England	2.58 (2.21, 2.96)
Midwest	2.10 (1.96, 2.24)
South	2.24 (2.02, 2.46)
West	2.41 (2.05, 2.76)
Year of diagnosis	
2011-2012	2.28 (2.04, 2.51)
2013-2014	2.30 (2.13, 2.46)
2015-2016	2.29 (2.15, 2.42)
AVR, aortic valve replacement; CI, confidence interval; MOR, median odds ratio	

Table S8. Full multi-level logistic models for the likelihood of AVR (vs. no AVR) and the likelihood of TAVR (vs. SAVR).

Patient Characteristics	AVR vs non-AVR		TAVR vs SAVR	
	HR (95% CI)	P-value	HR (95% CI)	P-value
Gender				
Male	Reference		Reference	
Female	0.76 (0.70, 0.83)	<.0001	1.46 (1.28, 1.65)	<.0001
Age				
<65	Reference		Reference	
65-79	1.01 (0.88, 1.17)	0.1940	3.90 (3.07, 4.93)	<.0001
80+	0.52 (0.45, 0.61)	<.0001	20.83 (16.25, 26.69)	<.0001
Race				
Non-Hispanic white	Reference		Reference	
Non-Hispanic black	0.72 (0.57, 0.91)	0.0070	1.06 (0.73, 1.53)	0.7746
Asian	0.66 (0.35, 1.26)	0.2064	1.12 (0.52, 2.40)	0.7748
Hispanic	0.93 (0.71, 1.22)	0.5975	0.69 (0.47, 1.03)	0.0630
Other/unknown	0.86 (0.69, 1.07)	0.1690	1.03 (0.74, 1.43)	0.8624
Division				
East North Central	Reference		Reference	
East South Central	2.01 (1.52, 2.66)	<.0001	1.28 (0.81, 2.02)	0.2933
Middle Atlantic	1.31 (0.99, 1.74)	0.0626	1.74 (1.10, 2.74)	0.0173
Mountain	2.01 (1.47, 2.75)	<.0001	0.53 (0.32, 0.9)	0.0176
New England	0.72 (0.52, 1.01)	0.0575	1.82 (0.96, 3.45)	0.0685
Pacific	0.95 (0.74, 1.24)	0.7266	1.25 (0.80, 1.96)	0.3272
South Atlantic/West South Central	1.24 (1.02, 1.49)	0.0267	1.43 (1.04, 1.97)	0.0298
West North Central	1.19 (1.01, 1.41)	0.0391	0.80 (0.60, 1.08)	0.1395
Other/unknown	1.05 (0.8, 1.39)	0.7221	0.89 (0.51, 1.56)	0.6939
Income level (quantiles)*				
<20th	Reference		Reference	
20th-40th	0.97 (0.82, 1.14)	0.7060	0.99 (0.73, 1.36)	0.9701
40th-60th	1.06 (0.90, 1.24)	0.4766	1.14 (0.86, 1.51)	0.3665
60th-80th	1.02 (0.87, 1.21)	0.7798	1.19 (0.88, 1.62)	0.2662
80th+	1.13 (0.93, 1.36)	0.2191	1.20 (0.84, 1.71)	0.3217
Education level (quantiles)				
<20th	Reference		Reference	
20th-40th	1.10 (0.93, 1.30)	0.2718	0.87 (0.64, 1.19)	0.3910
40th-60th	0.92 (0.79, 1.07)	0.2694	0.76 (0.58, 1.01)	0.0577
60th-80th	0.95 (0.82, 1.10)	0.4815	0.82 (0.62, 1.08)	0.1517
80th+	0.90 (0.76, 1.07)	0.2302	0.95 (0.69, 1.31)	0.7581
Insurance				
Medicare	Reference		Reference	
Commercial	1.24 (1.09, 1.41)	0.0007	0.81 (0.64, 1.03)	0.0911

|				
Medicaid	0.91 (0.71, 1.18)	0.4850	1.32 (0.78, 2.25)	0.3010
Uninsured	1.10 (0.83, 1.46)	0.5212	0.99 (0.57, 1.71)	0.9606
Other or Unknown	1.27 (1.15, 1.42)	<.0001	1.01 (0.83, 1.22)	0.9559
Charlson Comorbidity Index				
0	Reference		Reference	
1	1.02 (0.90, 1.16)	0.7559	1.26 (0.98, 1.61)	0.0693
2	0.98 (0.85, 1.14)	0.7946	1.65 (1.24, 2.20)	0.0006
3	0.94 (0.79, 1.11)	0.4568	1.84 (1.31, 2.57)	0.0004
4+	0.81 (0.66, 1.00)	0.0463	2.43 (1.61, 3.67)	<.0001
Atrial fibrillation	0.74 (0.68, 0.81)	<.0001	1.02 (0.85, 1.21)	0.8640
Cancer	0.94 (0.82, 1.08)	0.3595	0.97 (0.75, 1.27)	0.8347
Conduction	0.96 (0.85, 1.09)	0.5248	0.98 (0.76, 1.25)	0.8550
COPD	0.82 (0.72, 0.94)	0.0047	1.21 (0.93, 1.59)	0.1608
Dementia	0.33 (0.23, 0.46)	<.0001	1.58 (0.70, 3.57)	0.2686
Diabetes with complications	1.02 (0.87, 1.21)	0.7862	0.87 (0.63, 1.19)	0.3695
Diabetes without complications	1.00 (0.91, 1.11)	0.9602	1.04 (0.86, 1.26)	0.6675
Prior myocardial infarction	0.95 (0.84, 1.08)	0.4717	1.14 (0.88, 1.47)	0.3142
Osteoarthritis	0.99 (0.89, 1.11)	0.9189	0.91 (0.74, 1.12)	0.3742
Peripheral vascular disease	0.94 (0.84, 1.05)	0.2565	0.89 (0.72, 1.10)	0.2676
Heart failure	0.96 (0.86, 1.07)	0.4753	1.35 (1.10, 1.66)	0.0040
Moderate to severe renal disease	0.88 (0.77, 1.01)	0.0754	0.76 (0.58, 1.00)	0.0465
Smoking status				
Previous	Reference		Reference	
Current	1.05 (0.93, 1.20)	0.4339	0.84 (0.65, 1.09)	0.1990
Never	1.00 (0.92, 1.10)	0.9229	0.85 (0.72, 1.01)	0.0621
Use of supplemental oxygen	0.63 (0.52, 0.77)	<.0001	3.35 (2.14, 5.27)	<.0001
Percutaneous coronary intervention	1.05 (0.85, 1.31)	0.6539	2.28 (1.50, 3.47)	0.0001
Pacemaker	0.98 (0.72, 1.34)	0.8858	1.22 (0.63, 2.38)	0.5566
Hemodialysis	0.81 (0.56, 1.17)	0.2628	0.78 (0.32, 1.88)	0.5742
Dyspnea	1.65 (1.40, 1.94)	<.0001	1.16 (0.83, 1.62)	0.3778
Dyspnea on exertion	1.46 (1.31, 1.63)	<.0001	1.12 (0.92, 1.35)	0.2671
Angina	1.22 (1.12, 1.33)	<.0001	0.89 (0.76, 1.05)	0.1717
Syncope	0.90 (0.82, 0.98)	0.0153	1.13 (0.96, 1.34)	0.1388
Ejection fraction				
50+	Reference		Reference	
<34	0.66 (0.58, 0.76)	<.0001	1.40 (1.05, 1.86)	0.0213
35-49	0.80 (0.72, 0.90)	0.0002	1.42 (1.13, 1.78)	0.0022
Creatinine				
<0.9	Reference			
1.0-1.4	0.95 (0.87, 1.04)	0.2960	Reference	
1.5-1.9	0.73 (0.63, 0.84)	<.0001	2.44 (1.81, 3.28)	<.0001
2.0+	0.50 (0.41, 0.60)	<.0001	3.40 (2.28, 5.08)	<.0001
BMI				

20.1-25.0	Reference		Reference	
<20.0	0.65 (0.52, 0.81)	0.0001	1.99 (1.20, 3.32)	0.0080
25.1-30.0	1.36 (1.22, 1.51)	<.0001	0.88 (0.71, 1.09)	0.2436
30.1+	1.52 (1.37, 1.70)	<.0001	0.98 (0.79, 1.22)	0.8903
Year of diagnosis				
2011	Reference		Reference	
2012	1.61 (1.34, 1.93)	<.0001	3.19 (1.71, 5.98)	0.0003
2013	1.98 (1.67, 2.36)	<.0001	8.61 (4.81, 15.44)	<.0001
2014	2.28 (1.92, 2.71)	<.0001	14.36 (8.04, 25.64)	<.0001
2015	2.90 (2.45, 3.43)	<.0001	23.24 (13.06, 41.33)	<.0001
2016	3.52 (2.97, 4.19)	<.0001	39.34 (22.01, 70.32)	<.0001
Diagnosed in inpatient	0.62 (0.56, 0.69)	<.0001	1.35 (1.11, 1.65)	0.0032
Hospitalized in year prior	0.72 (0.65, 0.79)	<.0001	0.83 (0.68, 1.02)	0.0802
Median odds ratio for cardiologist	2.11 (1.99, 2.23)	<.0001	2.38 (2.13,2.63)	<.0001

*Income is available within the dataset at the zip code level, and not at the patient level
AVR, aortic valve replacement; BMI, body mass index; CI, confidence interval; COPD, chronic obstructive pulmonary disease; HR, hazard ratio; MOR, median odds ratio; SAVR, surgical aortic valve replacement; ssAS, symptomatic severe aortic stenosis; TAVR, transcatheter aortic valve replacement

Table S9. Median odds ratio (MOR) for general cardiologists for the likelihood of AVR when stratified by region and time.

Stratification	MOR for AVR (95% CI)
	Patients with available values for ejection fraction, creatinine, and body mass index
Region	
New England	2.38 (2.13, 2.63)
Midwest	2.00 (1.84, 2.15)
South	2.16 (1.89, 2.42)
West	2.16 (1.76, 2.54)
Year of diagnosis	
2011-2012	2.16 (1.76, 2.54)
2013-2014	2.14 (1.94, 2.33)
2015-2016	2.20 (2.03, 2.36)
AVR, aortic valve replacement; CI, confidence interval; MOR, median odds ratio	

Figure S1. Kaplan-Meier curves for survival when stratified by severity of aortic stenosis.
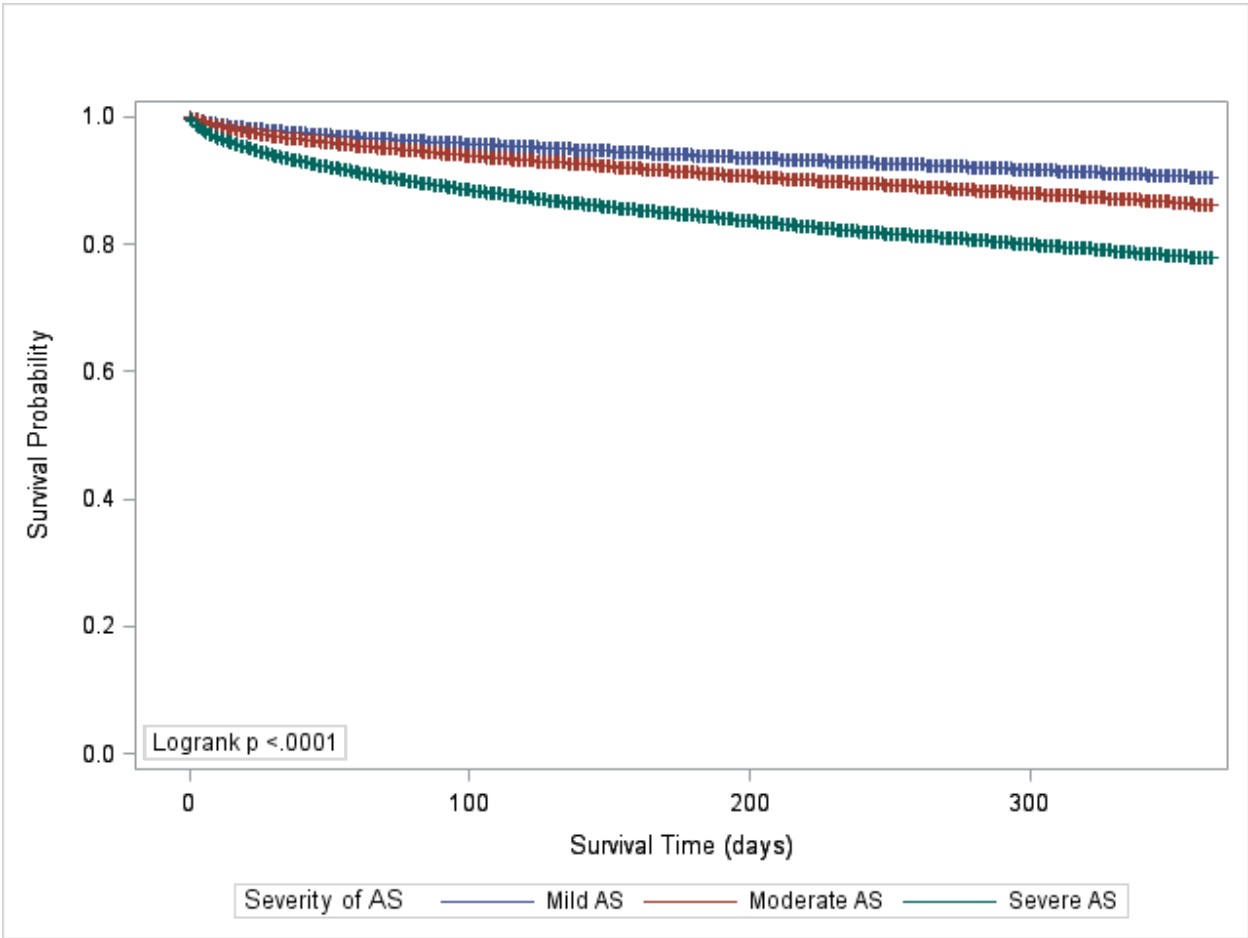
AS, aortic stenosis

Figure S2. Association between clinician 1-year treatment rate and 1-year all-cause mortality in patients with lab data

The distribution of cardiologists by 1-year AVR rate is shown below the curve with each strike representing an individual clinician
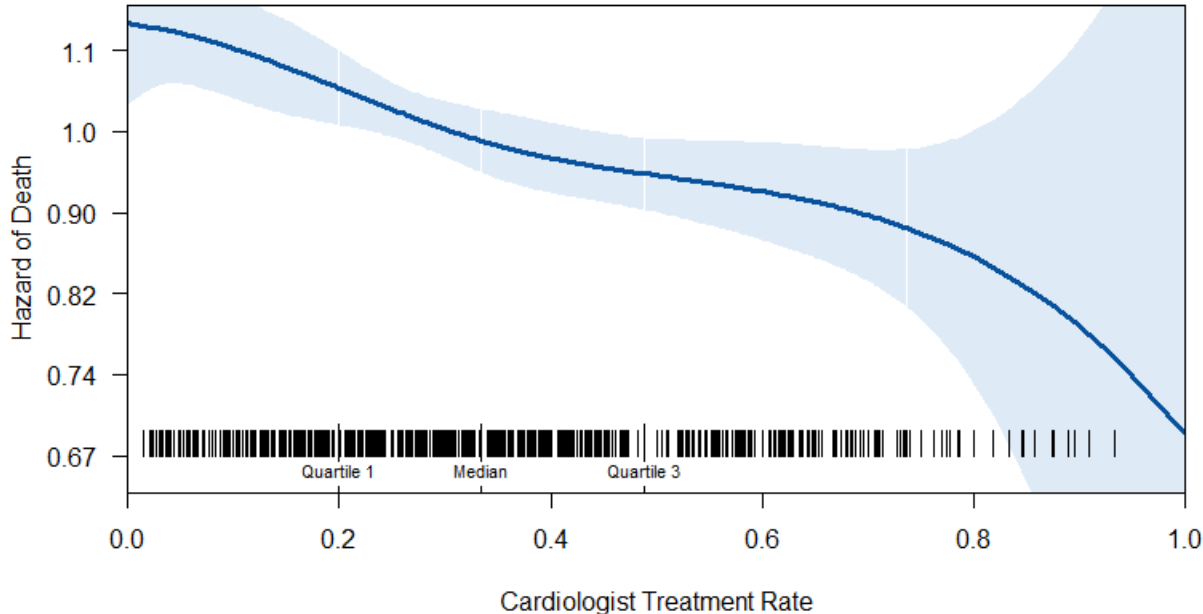
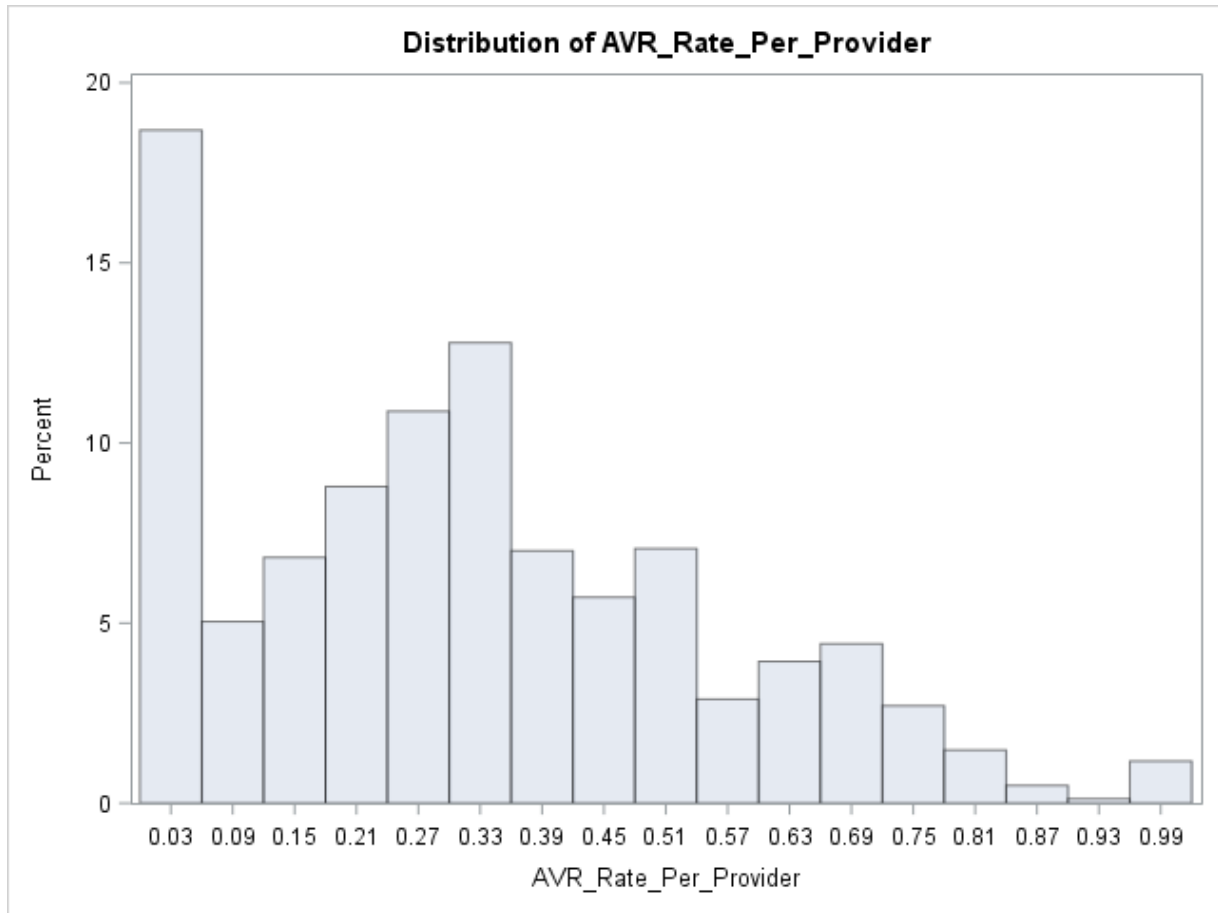**Figure S3. Histogram showing the AVR intervention rate by cardiologist within 1 year**

Distribution of AVR_Rate_Per_Provider

Figure S4. Cardiologist AVR treatment rate stratified by quartile

Cardiologists were ranked by treatment rate with cardiologist quartiles indicated by color (1 represents the lowest quartile of cardiologists in terms of AVR rate and 4 the highest).
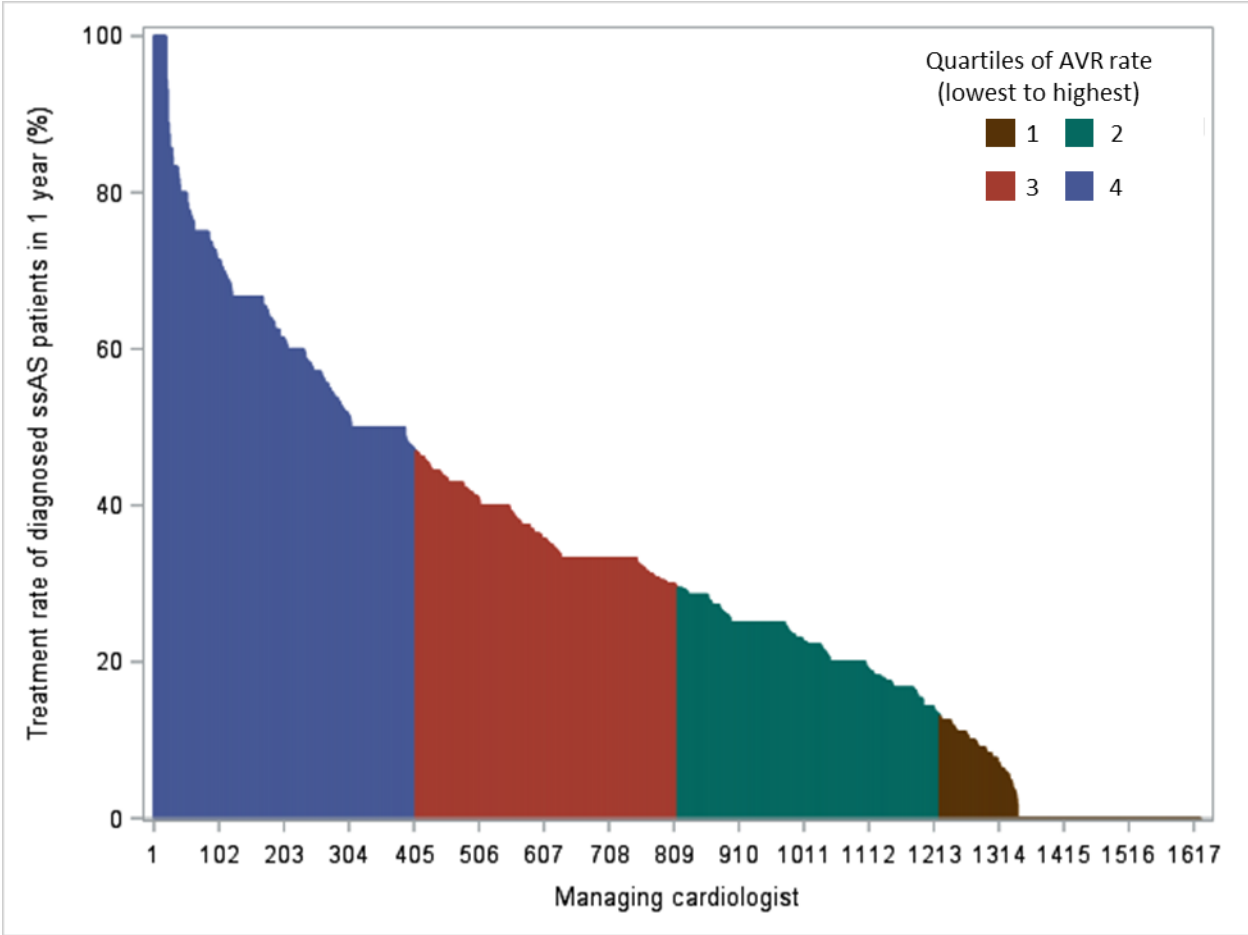
Figure S5. Clinician's AVR rate compared to TAVR rate for ssAS patients

Scatter plot for a cardiologist's AVR rate as compared to their TAVR rate for ssAS patients. There was a significant correlation between AVR rate and TAVR rate. The smoothing curve was applied to the data to better visualize trends.

AVR, aortic valve replacement; ssAS, symptomatic severe aortic stenosis; TAVR, transcatheter aortic valve replacement
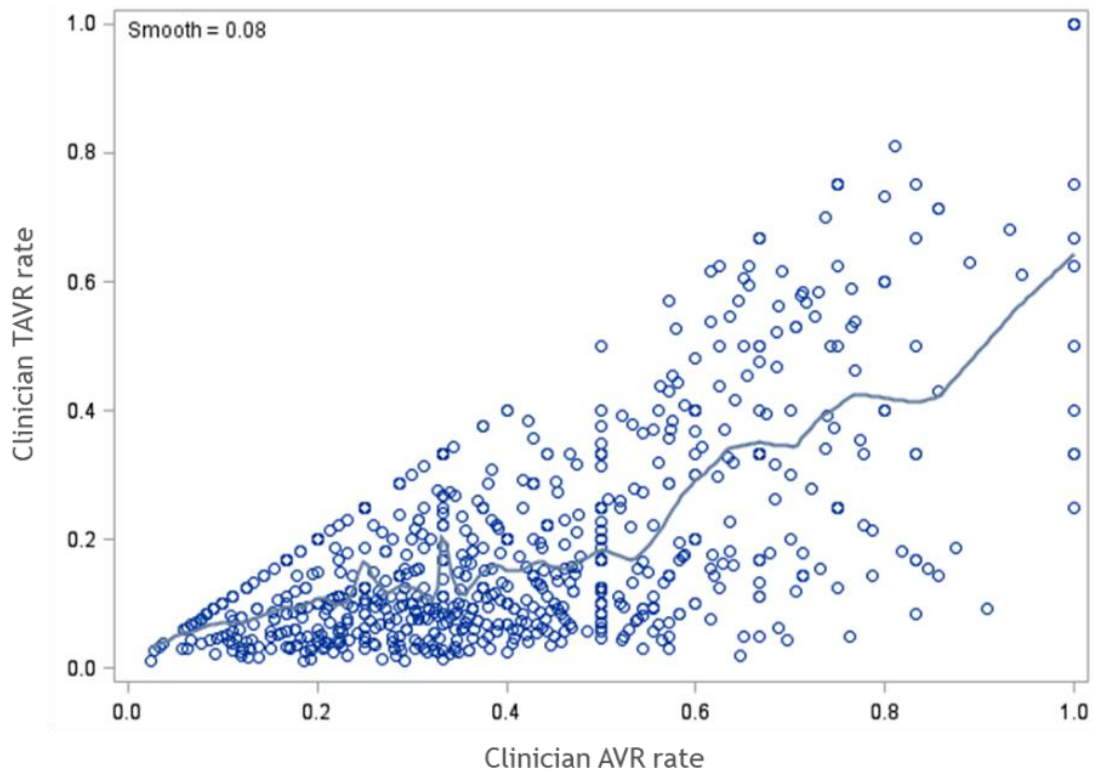
Figure S6. Association between managing cardiologists' 3-month AVR treatment rate and 1-year all-cause mortality with clinician 3-month treatment
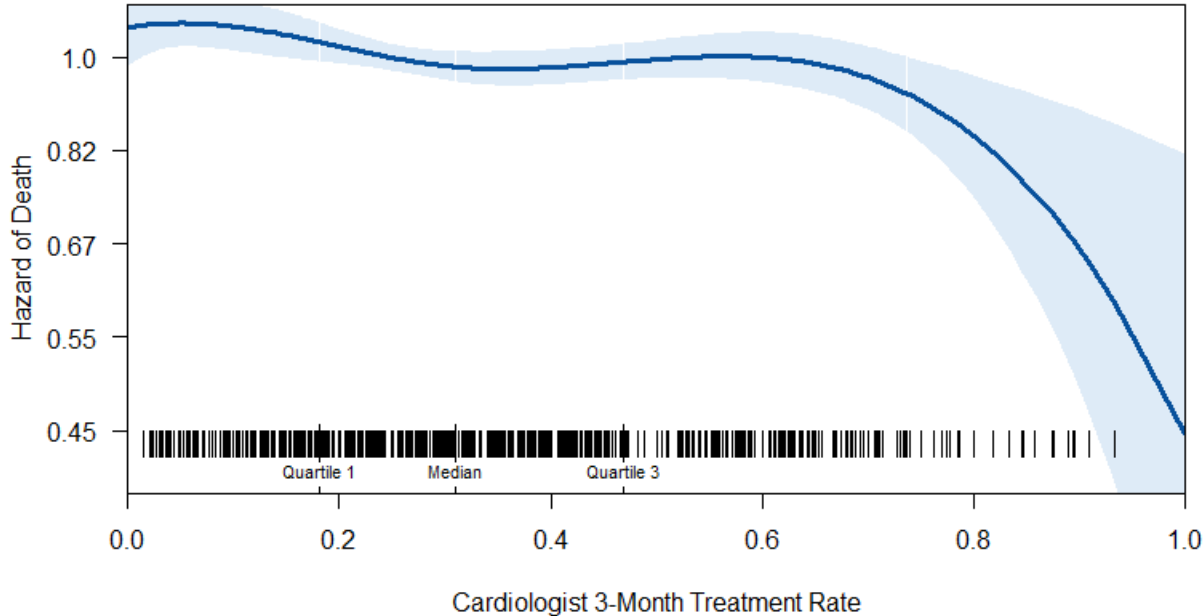
Figure S7. Kaplan-Meier curves for survival when stratified by managing cardiologist 3-month AVR treatment rate