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ABSTRACT

BACKGROUND

The 2014 American Heart Association/American College of Cardiology Valvular Heart Disease Guidelines state that mitral valve diseases should be repaired at a Center of Excellence (CoE). We evaluate the cost-effectiveness of such referrals.

METHODS

We estimate patients' life expectancy based on projected survival of patients after mitral valve surgery and develop a cost model to calculate short- and long-term benefits and costs to both patients and payers. Benefits include increased life expectancy and avoidance of medical complications for patients. Short-term costs include all upfront payments by patients and payers at the time of discharge. Long-term costs include all payments associated with the condition that prompted the surgical procedure incurred during the remainder of a patient's life. We assess cost-effectiveness of treating patients with various ages and major comorbidities at CoEs vs non-CoEs.

RESULTS

Full implementation of the guidelines would result in an increase in the percentage of patients obtaining mitral valve repair instead of valve replacement from 58% to 72%. Depending on the patient's age and comorbidities, it would also result in a 6.64% to 12.47% reduction in mortality, 7.85% to 9.97% reduction in reoperation, 9.97% to 17.16% reduction in stroke, and an average gain of 3.77 to 9.88 months of life expectancy. Finally, greater reliance on CoEs results in financial savings to payers, due to avoidance of the costs of future complications.

CONCLUSION

Patients benefit from mitral valve surgery at a CoE regardless of their age or comorbidities. Payers may incur additional short-term costs when patients are referred to a CoE, but these are fully offset by long-term savings at the current repair rate gap of 24% between CoEs and non-CoEs in New York State. Redesigning co-pay structures and/or refining the set of patients who are referred to CoEs could further align the incentives of patients and payers on a case-by-case basis and achieve an even more desirable social outcome.

Mitral valve disease is one of the most common forms of heart valve diseases in US, affecting 5% of the population and resulting in 500,000 hospital admissions per year.[i] Mitral valve repair and replacement are two different cardiac surgical operations used to treat stenosis or regurgitation of the mitral valve. Existing literature indicates that mitral valve repair is superior to mitral valve replacement for degenerative mitral insufficiency because it offers better survival, fewer complications and lower costs.[1,2,3,4]

For purposes of our analysis, we define a Center of Excellence (CoE) as a medical center whose repair rate is statistically significantly higher than state or national average. Six hospitals are identified as CoEs in New York relative to the state average (see Figure S1 in the Supplementary Appendix).[5] Despite the strong reputation of CoEs, our analysis of 2,718 patients with elective mitral valve diseases in New York from 2009-2012 shows that only 40.4% were treated at a CoE for mitral valve surgery. We estimate the average risk-adjusted repair rate to be 70% at CoEs and 46% at non-CoEs, which implies that 389 patients who could have had their mitral valve repaired instead received a less desirable valve replacement.

Recently, the 2014 American Heart Association/American College of Cardiology Valvular Heart Disease Guidelines called for referrals of patients to a CoE for a higher chance of repair.[ii] The main objective of this study is to estimate the incremental health gains as well as costs and benefits to payers of this type of referral strategy.

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[i] http://heartvalvedisease.nm.org/mitral-valve-disease.html

[ii] Thoracic Surgery News, Nov 2014.

METHODS

HOSPITAL QUALITY AND PATIENT CHOICE

This study uses data from the New York State Inpatient Database, which includes 10 million discharges from all hospitals in New York State between 2009 and 2012. We identified discharges related to isolated mitral valve procedures through its clinical codes 35.12, 35.13 and 35.24 based on International Classification of Disease (9^{th} revision) and focused on only elective cases. Patients were excluded if they were less than 30 years old, had coronary revascularization, congenital heart disease, excision of ventricular aneurysm, replacement of thoracic aorta, aortic fenestration procedure, closed heart valvuloplasty, heart transplant, or other valvular repair or replacement.[6] Patients were also excluded if they travelled from other states to New York or if they were Native American (less than 1% of the sample). This resulted in 2,718 patients treated in 35 hospitals over the four year interval.

To measure the gap in repair rates between CoEs and non-CoEs, we used a probit model with procedure type (i.e., repair or replacement) as the dependent variable. Included in the probit model were independent variables of patients' demographics, insurance type and comorbidities. Since patients are not randomly assigned to hospitals, we cannot directly compare observed repair rates between hospitals. To correct for a potential selection bias if patients who are more likely to benefit from a CoE were also more likely to choose a CoE, we constructed a distance-based instrumental variable, which correlates with the probability of choosing a CoE but not with patient characteristics.[7]

To understand which factors affect patients' choices of hospitals, we used a probit model with the choice of a CoE vs a non-CoE as the dependent variable. The independent variables are patient demographics, insurance type, extra travel distance to the nearest CoE and a dummy indicating whether the patient has a local CoE (i.e., within 5 miles to the nearest hospital).

COST-BENEFIT MODEL

To evaluate the impact of hospital choice, we constructed a model to characterize short- and long-term costs to both patients and payers. Based on the steps and contingencies associated with mitral valve diseases (see Figure S2 in the Supplementary Appendix for a schematic), our model includes: (1) travel cost, (2) procedure cost, (3) cost of reoperation, (4) cost of stroke, (5) cost of bleeding, (6) cost of maintenance (i.e., warfarin for anticoagulation) for mechanical valve replacement, and (7) cost of Structural Valve Deterioration (SVD) for biological valve replacement. We estimated these costs for patients without comorbidities (which we refer to as "standard" patients) and for patients with common comorbidities, including heart failure, chronic lung disease, diabetes, hypertension, renal disease, and atrial fibrillation.[4]

We calculated costs to patients associated with treatment in a given hospital as:

Costs to Patients = Cost of Operative Mortality + Cost of Long-term Survival + Cost of Reoperation + Cost of Stroke + Cost of Bleeding + Cost of Maintenance + Cost of SVD + Travel Cost

where each term is measured as the expected change in Quality Adjusted Life Years (QALY) induced by the procedure. For example, Cost of Operative Mortality refers to expected loss of QALY caused by the possible outcome of operative death.

Similarly, we computed costs to payers as:

Costs to Payers = Procedure Cost + Cost of Reoperation + Cost of Stroke + Cost of Bleeding + Cost of Maintenance + Cost of SVD

where costs over time were converted to net present value of payments using a 5% discount rate.[iii]

Finally, for both patients and payers, we computed *the net benefit from a CoE* as the difference between the expected cost at a non-CoE hospital and that at a CoE.

MODEL ELEMENTS

Because no single source or paper contains all the data required in our model, we drew from several sources in the medical literature to estimate the needed parameters. When necessary, we supplemented the literature review with estimates from existing datasets including Society of Thoracic Surgeons (STS) National Database and National Inpatient Sample Data. All costs and benefits were converted into 2014 US dollars. Table 1 summarizes the sources for each model element for patients of different ages, with and without comorbidities.

[iii] http://www.irs.gov/irb/2014-47_IRB/ar12.html

Table 1. **Sources of Model Elements**

Model Elements	**Resources***
Repair Rate	Daneshmand et al. 2010[2], Vassileva et al. 2013[4]
Operative Mortality	STS Risk Calculator, NIS 2008-2012†
Long-term Survival	Ray et al. 2006[8], Daneshmand et al. 2010[2], Gelsomino et al. 2011[9], Daneshmand et al. 2009[10]
Procedure-related Reoperation	Dumon et al. 2007[11], STS Risk Calculator
Stroke	Russo et al. 2008[12], National Institute of Neurological Disorders and Stroke
Bleeding	Keneko et al. 2014[13], Chikwe et al. 2011[14], Ailawadi et al. 2008[15], LaPar et al. 2010[3]
Maintenance	http://health.costhelper.com/valve-replacement.html
Structural Valve Deterioration	Bourguignon et al. 2014[16]
Procedure Cost	Medicare Provider Utilization and Payment Data, NIS 2008-2012
Travel Cost	Paulsen et al. 2015[17]

*A detailed literature review is provided in the Supplementary Appendix.

†STS Risk Calculator incorporates the STS risk models that are designed to serve as statistical tools to account for the impact of patient risk factors on operative mortality and morbidity. National Inpatient Sample database is the largest U.S. database of inpatient hospitals that incorporates data from all payers.

RESULTS

HOSPITAL QUALITY

The likelihood of receiving a repair is influenced by both hospital and patient characteristics. By definition CoEs had significantly higher repair rates (Table 2, middle column). After correcting for potential selection bias, our analysis shows that visiting a CoE instead of a non-CoE resulted in an average increase in the probability of mitral valve repair of around 24%. However, several patient characteristics, including old age, female gender, chronic lung disease, diabetes, and renal failure directly reduced the chance of mitral valve repair. Other patient characteristics, such as non-white race and having Medicare or Medicaid coverage, reduced the likelihood of receiving a mitral valve repair indirectly by reducing the probability of choosing a CoE.

Table 2. Impact of Patient Characteristics, Comorbidities, Payer and Distance

		On MV Repair Rate†			On Choice of A CoE††		
Category	**Variables**	**Coeff.**		**S.E.**	**Coeff.**		**S.E.**
Demographics	Age	-0.019	***	0.003	-0.005		0.003
	Female	-0.281	***	0.052	0.001		0.054
	Black	-0.236	**	0.101	-0.180	*	0.103
	Hispanic	-0.367	***	0.117	-0.291	**	0.121
	Asian	-0.455	**	0.191	-0.528	***	0.193
	Others	-0.061		0.090	0.552	***	0.081
Payer	Medicare	-0.163	**	0.074	-0.184	**	0.077
	Medicaid	-0.251	**	0.109	-0.518	***	0.114
	Self	-0.536		0.341	-0.217		0.374
	Other	0.284		0.197	-1.068	***	0.263
Comorbidities	Heart Failure	-0.103		0.326	0.000		0.328
	Lung Disease	-0.229	***	0.068	0.110		0.073
	Diabetes	-0.180	***	0.069	-0.048		0.074
	Hypertension	0.074		0.054	-0.045		0.056
	Renal Disease	-0.256	***	0.087	-0.089		0.094

	Atrial Fibrillation	-0.100	*	0.053	0.011		0.055
Proximity	Extra Dist. to CoE				-0.025	***	0.002
	CoE in 5 Miles				0.202	***	0.066
CoE		0.724	***	0.140			
	Constant	1.521	***	0.183	0.483	***	0.182

*** p<0.01, ** p<0.05, * p<0.1

†A probit model was used for the analysis of MV repair rate. The dependent variable is whether a patient received mitral valve repair. Independent variables are patient demographics, insurance type, comorbidities, and a dummy for CoEs. The baseline group has the following characteristics: male, white, private insurance, and no comorbidities. Distance is used as an instrument for CoEs to correct for the potential selection bias that patients who choose a CoE are also those who are more likely to benefit from a CoE.

††A probit model was used for the analysis of patient choice of a CoE vs a non-CoE. The dependent variable is whether a patient chose a CoE. Independent variables are patient demographics, insurance type, comorbidities, distance and proximity to a CoE. The baseline group has the following characteristics: male, white, private insurance, no comorbidities, and no CoE in 5 miles.

PATIENT CHOICE

Among the 2,718 patients in our analysis, 1,097 (40.4%) chose a CoE (see Table 3). This percentage strongly correlates with patients' distance to the nearest CoE, suggesting distance is an important factor affecting how patients chose hospitals. Among the 1,154 patients who had a CoE within 5 miles from their nearest hospital, 61.2% chose a CoE. Among those who did not have a CoE within 5 miles from their nearest hospital, only 38.8% chose a CoE. Patients who chose CoEs were younger (64.3 vs 65.4, p-value of 0.020). Compared with CoEs, non-CoEs treated a higher percentage of white patients (76.8% vs 66.5%, p-value of 0) and Asian patients (2.4% vs 1.3%, p-value of 0.037), a higher percentage of patients with Medicare (52.6% vs 48.0%, p-value of 0.019) and Medicaid (8.4% vs 5.3%, p-value of 0.002), and a lower percentage of patients with private insurance (35.8% vs 45.7%, p-value of 0). There was no significant difference between CoEs and non-CoEs in terms of patients' gender.

Table 3. Characteristics of Patients Treated at CoEs and non-CoEs*

Variable	Non-CoE	CoE†	P-Value
Age (mean)	65.4	64.3	0.020
Below 50	11.5% (186)‡	13.5% (148)	0.059
50-60	19.8% (321)	21.7% (238)	0.110
60-70	27.2% (440)	26.9% (295)	0.439
70-80	28.0% (454)	25.4% (279)	0.068
Above 80	13.6% (220)	12.5% (137)	0.204
Gender			
Female	45.5% (738)	43.8% (481)	0.388
Male	54.5% (883)	56.2% (616)	0.388
Race			
White	76.8% (1245)	66.5% (730)	0
Black	7.8% (127)	7.1% (78)	0.483
Hispanic	5.9% (95)	4.3% (47)	0.070
Asian	2.4% (39)	1.3% (14)	0.037
Other Race	7.1% (115)	20.8% (228)	0
Payer			
Medicare	52.6% (853)	48.0% (527)	0.019
Medicaid	8.4% (136)	5.3% (58)	0.002
Private	35.8% (580)	45.7% (501)	0
Self-Payer	0.5% (8)	0.5% (6)	0.849
Other	2.7% (44)	0.5% (5)	0
Extra Distance to CoE			

Less than 5 miles	29.8% (483)	61.2% (671)	0
More than 5 miles	70.2% (1138)	38.8% (426)	0
Total Number	59.6% (1621)	40.4%(1097)	

*This summary is based on New York State Inpatient Database 2009-2012.
†This study includes 35 NY hospitals, out of which 6 have risk adjusted repair rates that are significantly higher than the average of all hospitals in New York. These six hospitals are called CoEs in this study.
‡Percentage of patients in each age group and number of cases (in bracket).

Table 2 (right column) summarizes the estimation results of the patient choice model and shows how patient characteristics, insurance type, travel distance and proximity to a CoE affected the likelihood of choosing a CoE. We see that, compared with white patients, Hispanic and Asian patients were less likely to choose a CoE. Compared with patients with private insurance coverage, those with Medicare, Medicaid and other payers were also less likely to choose a CoE. The probability of choosing a CoE decreased as the extra travel distance to the nearest CoE increased. Whether a patient had a local CoE significantly affected his/her likelihood of choosing a CoE. But we did not find gender and comorbidities to play a significant role in affecting patients' choice of a CoE.

LIFE EXPECTANCY

Our model estimates that the life expectancy a patient gained from going to a CoE instead of a non-CoE ranged from 3.77-9.88 months depending on the patient's age and comorbidities (Table 4, top). Generally speaking, patients in their 70s benefited the most. However, existence of comorbidities reduced the benefits from a CoE for all age groups. The relationship between patients' age and benefits is not linear, because younger patients were more likely to receive a mechanical valve replacement, which is both more durable and more hazardous (with respect to stroke risk) than a biological valve.

We converted life expectancy into monetary value using the formula 1000k × $age^{-0.66}$.[18] For patients with mitral valve replacement, this number was further discounted by yearly mortality rates associated with biological or mechanical valve replacement. The results are summarized in Table 4 (middle). This shows that patients' benefit ranged from $7,548 (for patients in their 80s with heart failure) to $28,508 (for patients in their 70s with no comorbidities).

Table 4. Savings to Patients and Payers*

	Age Group			
Comorbidities	50	60	70	80
Patient Life Expectancy (mo)**				
Standard	7.86	8.46	9.88	7.77
Hypertension	7.68	8.06	8.91	6.68
Heart Failure	5.43	6.34	5.35	3.77
Diabetes	6.14	6.37	7.11	5.18
Renal Disease	6.15	5.76	6.66	3.81
Atrial Fibrillation	5.64	5.54	5.77	4.10
Chronic Lung	5.97	6.28	7.08	5.24
Patient Monetary Savings†				
Standard	$23,857	$25,299	$28,508	$20,789
Hypertension	$24,443	$24,356	$25,556	$17,264
Heart Failure	$16,454	$18,407	$13,923	$7,548
Diabetes	$18,150	$18,384	$19,459	$12,497
Renal Disease	$18,684	$16,627	$15,609	$8,455
Atrial Fibrillation	$17,084	$16,018	$15,358	$8,732

Chronic Lung	$17,319	$17,906	$19,148	$12,747
Payer Monetary Savings‡				
Standard	$8,075	$7,076	$4,452	$2,417
Hypertension	$7,846	$6,846	$4,259	$2,158
Heart Failure	$6,903	$6,353	$4,239	$2,590
Diabetes	$5,708	$4,976	$2,879	$1,231
Renal Disease	$5,695	$4,939	$2,885	$1,379
Atrial Fibrillation	$6,348	$5,797	$3,635	$2,026
Chronic Lung	$5,699	$4,941	$2,889	$1,382

*All results are based on our findings that average repair rate of CoEs is 24% higher than that of non-CoEs. Related risk factors include operative mortality, long-term survival, reoperation, stroke, bleeding, maintenance (for mechanical valve) and structural valve deterioration (for biological valve). Green color indicates positive savings.

**Increase in life expectancy refers to the difference between life expectancy at CoEs and that at non-CoEs.

†Conversion of life expectancy to monetary value is based on the formula 1000k × $age^{-0.66}$. [18]

‡ Cost to payers refers to the difference between cost at CoEs and that at non-CoEs. We estimate that mitral valve repair costs $46,000 and mitral valve replacement costs $53,000 at non-CoE hospitals and both costs are $4,000 higher at CoEs.

COSTS TO THE PAYERS

Costs to payers also depend on a patient's age and comorbidities (Table 6, bottom). Estimating these costs by using the sources in Table 1 and our statistical estimates of the increased likelihood of receiving a repair from a CoE indicates that payers obtained positive savings through treatment at a CoE for patients of all age groups and all comorbidities. Per patient benefit to payers ranged from $1,231 (for patients in their 80s with diabetes) to $8,075 (for patients in their 60s with no comorbidities).

SOCIETAL BENEFIT

We calculated societal benefits by adding the net savings to patients and payers (See Table S1 in the Supplementary Appendix). Societal benefits were positive for all age groups and all comorbidities, ranging from $9,834 (for patients in their 80s with renal disease) to $32,959 (for patients in their 70s with no comorbidities).

DISCUSSION

Mitral valve repair is superior to mitral valve replacement for all age groups and all comorbidities for isolated degenerative mitral valve disease. Based on inpatient discharge data from New York State 2009-2012, our study suggests that CoEs have significantly higher repair rates than non-CoEs with an average gap in risk adjusted repair rate of around around 24%. Despite this, roughly 60% of patients in the New York cohort failed to choose a CoE, and therefore some of them missed the opportunity to receive medically beneficial mitral valve repairs. This study shows that distance and insurance type are two important factors affecting patients' choice of a CoE.

Our model predicts that referral of mitral patients to a CoE as outlined in the 2014 American Heart Association/American College of Cardiology Valvular Heart Disease Guidelines would benefit patients of all age groups and all comorbidities. However, the net savings vary widely for different age groups and different comorbidities, ranging from $7,548 to $28,508.

Directing patients to CoEs benefits payers as well, because long-term reductions in costs of complications are sufficient to offset the higher short-term procedure cost at a CoE. Therefore, the economic incentives of patients and payers align (Table 4). Presumably, better dissemination of information about the clinical and economic benefits of mitral valve surgery at a CoE would result in more of these patients going to a CoE.

We should note, however, that referring all patients to CoEs, as recommended by the Valvular Heart Disease Guidelines, could create longer travel distance and capacity problems for treatment at the CoEs. Our model predicts that, if patients were referred to the nearest CoE, overall repair rate would increase by 26%, patients would need to travel 11 miles further on average, and CoEs would experience 150% increase in volume. Furthermore, encouraging all patients to go to CoEs could retard the establishment and maintenance of proficiency of other hospitals.

Finally, the gap of repair rate between CoEs and non-CoEs is not uniform across patients of differing levels of case complexity, which suggests that the incentives of patients and payers are not necessarily aligned for each individual patient. Better prediction is needed to identify which patients are most likely to benefit from the sophistication and experience of a CoE. For instance, it may be possible for a cardiologist or surgeon to analyze the preoperative echocardiogram to estimate the repairability of a patient's mitral valve. For purposes of illustration, suppose that these estimates are classified into low, moderate and high and that outcome data for hospitals are stratified according to these classifications. Then, as illustrated in Figure 1, the repair rate gap between CoEs and non-CoEs is likely to be small for the low category (some patients will get their mitral valve repaired at a CoE or a non-CoE) and for the high category (some patients with unrepairable mitral valve will get a replacement even if they visit a CoE). Hence, neither patients in these categories nor their payers will have strong incentives to choose a CoE. But for the moderate repairability category, the gap between CoEs and non-CoEs will be sufficiently large to result in substantial benefits to both patients and payers. By routing only those patients who benefit most to CoEs, the limited capacity of CoEs will be applied in a manner that produces the greatest societal value.

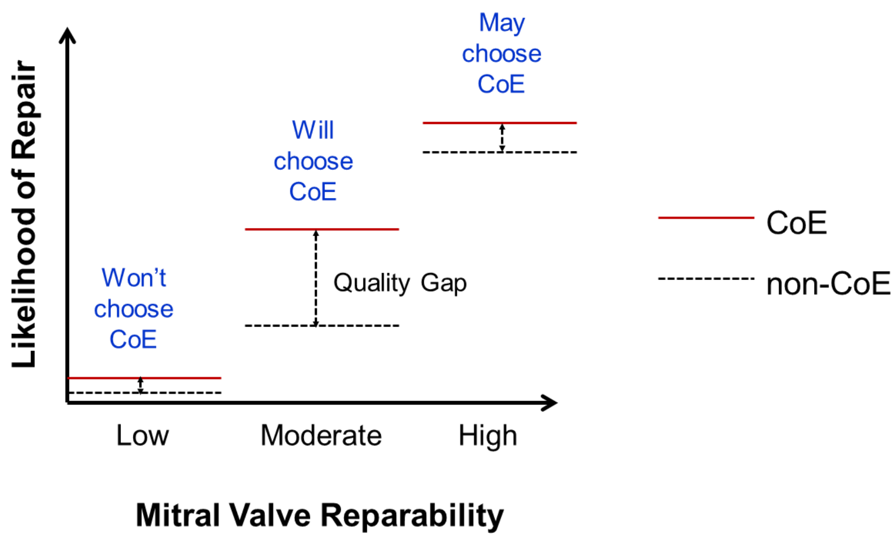

Figure 1. Mitral Valve Reparability & Quality Gap between CoEs and Non-CoEs

In conclusion, our results suggest that both patients and payers can benefit from referring mitral patients to CoEs. Under current conditions, such referral generally implies an increased short-term cost premium at CoEs. But these costs are overweighed by long-term savings to payers and substantial gains to patients. Making properly risk and selection bias adjusted outcome data widely available will lead to better provider selection, which in turn will result in improved long-term outcomes and a reduction in medical costs for patients with mitral valve disease.

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Supplementary Appendix

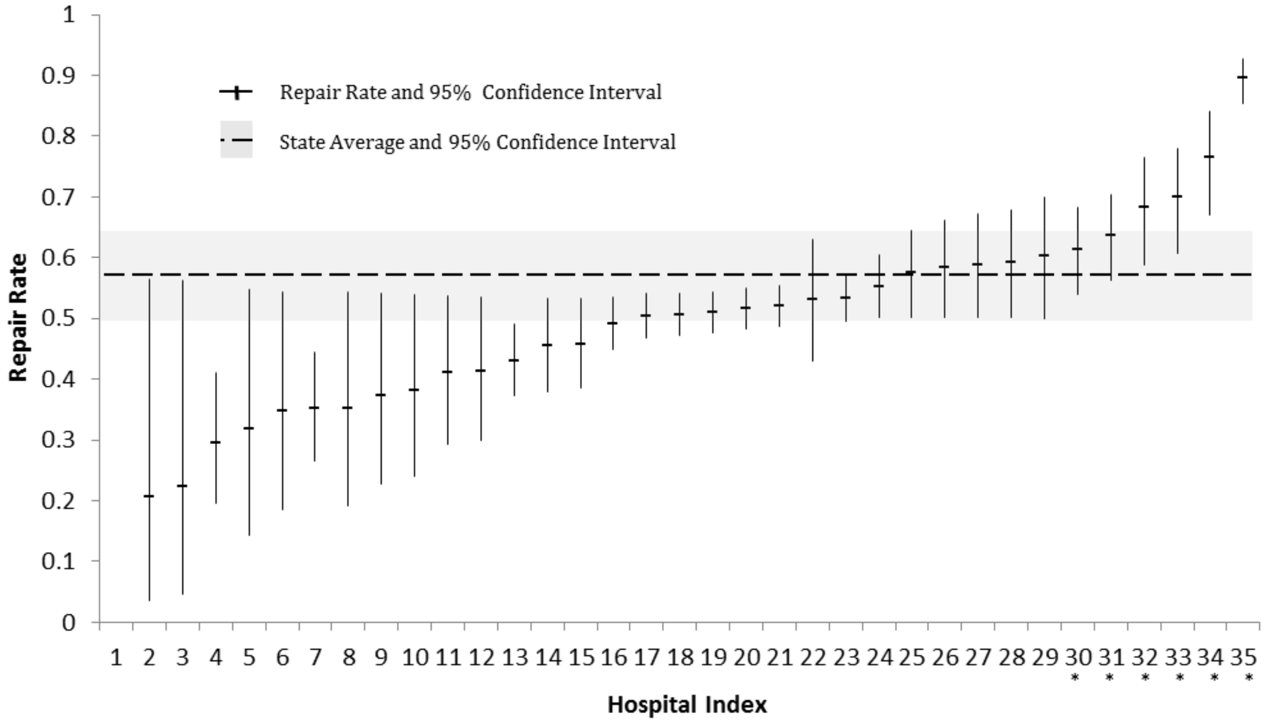

Figure S1: Mitral Valve Repair Rate of NY Hospitals†

† This figure is adopted from Wang, Li, Hopp, et al. (2015). A probit model was used for the analysis of MV repair rate. The dependent variable is whether a patient received mitral valve repair. Independent variables are patient demographics, comorbidities, hospitals' mitral volume, and hospital dummies. Distance is used as an instrument for mitral volume to correct for the potential selection bias that patients who choose high-volume hospitals are also those who are more likely to benefit from high-volume hospitals.

* Hospitals with indexes 30-35 have repair rates that are significantly higher than the average. These six hospitals are called CoEs in this study.

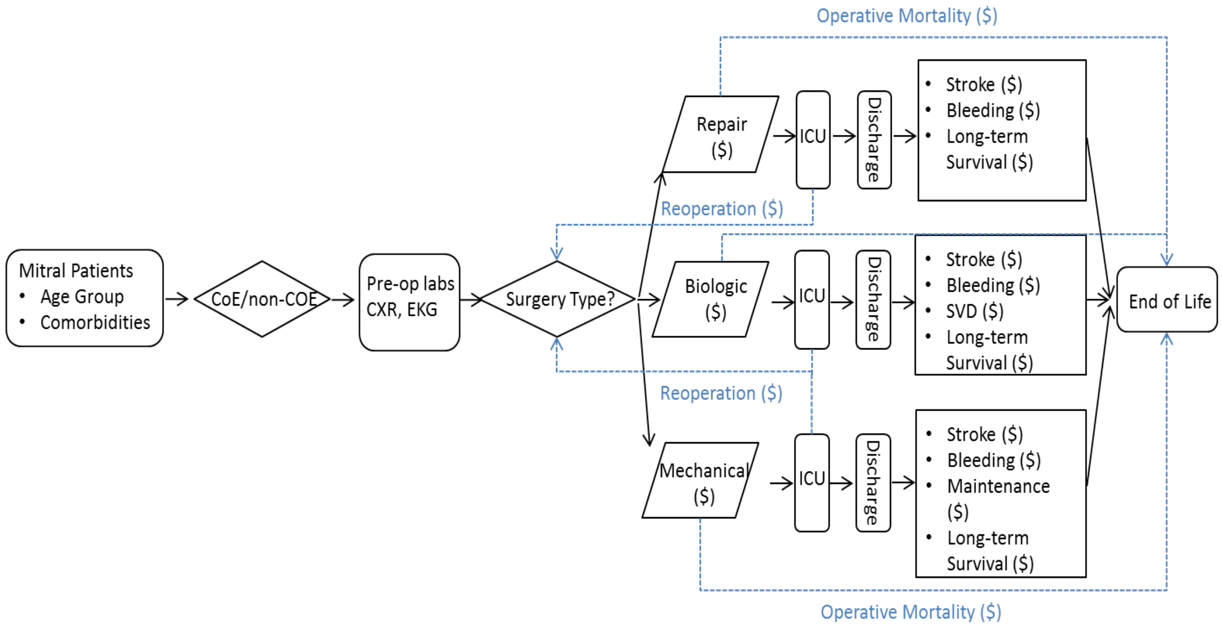

Figure S2: Related Events and Decision Process for Patients with Mitral Valve Diseases

MODEL ELEMENTS

There is no single source or paper that provides all the data required in our model. Therefore, we drew from several sources in the medical literature to estimate the various parameters. When necessary, we supplemented the literature review by estimates from existing datasets including Society of Thoracic Surgeons (STS) National Database and National Inpatient Sample Data. All costs and benefits have been converted into 2014 US dollars.

Below we discuss our estimates and sources of each model element for patients of different ages, with and without comorbidities. We consider common comorbidities including heart failure, chronic lung disease, diabetes, hypertension, and renal disease (Vassileva et al. 2013).[1]

Repair Rate: Our estimate of the impact of age on repair rate is based on Daneshmand et al. (2010), who studied 2,064 patients that underwent mitral surgeries from 1986 to 2006, and found that the probability of using a biological (over mechanical) valve is 20% for patients between 50 and 60, 36% for patients between 60 and 70, 71% for patients between 70 and 80 and 89% for patients above 80.[2] Impact of comorbidities on repair rate is estimated based on Vassileva et al. (2013), who studied 47,279 fee-for-service beneficiaries > 65 (from Medicare database) that underwent primary isolated mitral valve surgeries from 2000 to 2009, and found that the odds ratio is 1.23 for hypertension, 0.8 for diabetes, 0.78 for heart failure, 0.78 for chronic obstructive pulmonary disease and 0.8 for renal disease.[1]

Operative Mortality: Our estimate of operative mortality is based on the STS Risk Calculator, which incorporates the STS risk models that are designed to serve as statistical tools to account for the impact of patient risk factors on operative mortality and morbidity.[i] As the STS Risk Calculator does not provide separate results for biological and mechanical replacements, we used the National Inpatient Sample 2008-2012 to calculate them retrospectively. For patients aged 50-60, 60-70, 70-80 and over 80, we estimate operative mortality to be 0.24%, 0.44%, 0.79% and 1.61% for mitral valve repair, 0.37%, 0.36%, 1.03% and 2.91% for mechanical valve replacement, and 0.87%, 1.57%, 1.66% and 2.48% for biological valve replacement.

Long-term Survival: We estimated long-term survival of patients with mitral valve repair based on the US Social Security database, assuming that mitral valve repair restores patients' normal life expectancy (Ray et al. 2006).[3] Long-term survival associated with mitral valve replacement is estimated based on Daneshmand et al. (2010), who found that yearly mortality rate associated with biological valve replacement is 1.8 times that associated with mitral valve repair and yearly mortality rate associated with mechanical valve replacement is 1.3 times that associated with mitral valve repair.[2]

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[i] For more details, please see http://riskcalc.sts.org/stswebriskcalc/#/.

We estimated the impact of comorbidities on long-term survival by using the studies of Daneshmand et al. (2010), Gelsomino et al. (2011), Daneshmand et al. (2009).[2,4,5] The hazard ratio is 2.3 for atrial fibrillation, 1.3 for Chronic Obstructive Pulmonary Disease (COPD), 1.2 for diabetes, 2.1 for heart failure, 2.48 for renal disease, and 1.37 for hypertension.

Procedure-related Reoperation: We estimated the likelihood of procedure-related reoperation from the results of Dumont et al. (2007), who studied 188 patients that underwent reoperation for recurrent mitral regurgitation at the Cleveland Clinic from Jan 1980 to Jan 2005, and reported that around 90% of procedure-related reoperations occur in the first year.[6] For simplicity, we assumed all procedure-related reoperations occur in the first year. We estimated the impact of comorbidities on procedure-related reoperation by using the STS Risk Calculator. For patients aged 50-60, 60-70, 70-80 and over 80, we estimate procedure-related reoperation rate to be 4.38%, 5.21%, 6.19% and 7.41% for mitral valve repair, and 6.12%, 7.53%, 9.23% and 11.38% for mitral valve replacement.

Stroke: We estimated stroke rates based on Russo et al. (2008), who studied 1,344 patients that underwent mitral surgery at the Mayo Clinic from Jan 1980 to Dec 1995, and reported that (1) annual stroke rate is 1.15% for mitral valve repair, 2.7% for mechanical replacement and 1.65% for biological replacement; (2) 5-yr ischemic stroke rate is 6.1% for mitral valve repair, 16.1% for mechanical replacement and 8% for biological replacement; and (3) 10-yr ischemic stroke rate is 9.9% for mitral valve repair, 23.3% for mechanical replacement and 12.2% for biological replacement.[7] From their results, we calculated the ratio of stroke rates for biological replacement vs repair to be 1.65%/1.15%=1.4, and the ratio for mechanical vs biological replacement to be 2.7%/1.65%=1.6.

The impact of comorbidities on stroke was estimated based on National Institute of Neurological Disorders and Stroke.[ii] We estimated the age-adjusted hazard ratio to be 1.3 for diabetes and 2.5 for both heart failure and atrial fibrillation.

Bleeding: We estimated the rate of bleeding from Keneko et al. (2014), who studied a total of 768 patients with age <65 that underwent mitral valve surgeries from Jan 1991 to Jun 2012, and reported that there is no significant difference in the frequency of bleeding events between mechanical and biological valve replacements for patients younger than 65.[8] Chikwe et al. (2011), Ailawadi et al. (2008) and LaPar et al. (2010) reported that there is no significant difference in bleeding events between mitral valve repair and replacement.[9,10,11] Based on Keneko et al. (2014), we estimated freedom from major bleeding (same for mitral valve repair and replacement) at 5, 10, and 15 years to be 87.2%, 79.2%, and 71.2% respectively.[8] We were unable to find literature studying impact of comorbidities on bleeding and therefore used the same rates regardless of comorbidity.

Maintenance: We estimated costs of warfarin and associated risk event to be $1,500/yr (paid by payers).[iii] We also assumed that age and co-morbidities do not affect maintenance cost.

Structural Valve Deterioration (SVD): We estimated SVD rate based on Bourguignon et al. (2014), who studied 450 patients that underwent Carpentier-Edwards PERIMOUNT pericardial mitral bioprostheses from 1984 to 2011, and reported that the actuarial freedom from structural valve deterioration (SVD) at 20 years is 23.7%.[12]

[ii] http://www.ninds.nih.gov/disorders/stroke/preventing_stroke.htm
[iii] http://health.costhelper.com/valve-replacement.html

Procedure Cost: We estimated that mitral valve repair costs $46,000 and mitral valve replacement costs $53,000 at local non-CoEs, and the costs are $4,000 higher at CoEs, based on the Medicare Provider Utilization and Payment Data[iv] and National Inpatient Sample 2008-2012.

Travel Cost: We estimated travel cost to be $2,000 (paid by patient) in addition to loss of life years based on a patient survey conducted by the University of Michigan Cardiovascular Center (Paulsen, et al. 2015).[13]

Table S1. Societal Benefits from a CoE*

	Age Group			
Comorbidities	50	60	70	80
Standard	$31,933	$32,375	$32,959	$23,205
Hypertension	$32,289	$31,202	$29,815	$19,421
Heart Failure	$23,357	$24,760	$18,162	$10,138
Diabetes	$23,859	$23,360	$22,338	$13,728
Renal Disease	$24,379	$21,567	$18,494	$9,834
Atrial Fibrillation	$23,432	$21,815	$18,993	$10,758
Chronic Lung	$23,018	$22,847	$22,038	$14,129

* Societal benefit is the sum of patient benefits and payer benefits.

[iv] http://www.cms.gov/Research-Statistics-Data-and-Systems/Statistics-Trends-and-Reports/Medicare-Provider-Charge-Data/Inpatient.html

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