Impact of Surgical Experience on Operative Mortality After Reoperative Cardiac Surgery

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Background. **Learning curves and skill attrition with aging have been reported to impair outcomes in select surgical subspecialties, but their role in complex cardiac surgery remains unknown.**

Methods. **From 1986 to 2019, 2314 patients underwent reoperative cardiac surgery: coronary artery bypass grafting (n = 543), valve (n = 1527), or combined coronary artery bypass grafting and valve (n = 244). Thirty-four different surgeons in practice between 1 and 39 years were included. Standardized mortality ratio (observed-to-expected) was determined for all surgeons in each post-training year of experience.**

Results. **Risk-adjusted cumulative sum change-point analysis was used to define five distinct career phases: 0 to 4 years, 5 to 8 years, 9 to 17 years, 18 to 28 years, and 29 to 39 years. With 5 to 8 years and 18 to 28 years of experience, standardized mortality ratio was near unity (0.95 and 1.05, respectively) and lowest with 9 to 17 years of experience (0.78, $P = .03$). In the youngest experience group (0 to 4 years), observed and expected mortality were both highest, and standardized mortality ratio was elevated at 1.29, which approached statistical significance ($P = .059$). In the oldest experience group (29 to 39 years), expected mortality was low compared with most other groups but observed mortality increased, yielding a significantly elevated standardized mortality ratio at 1.53 ($P = .032$).**

Conclusions. **Standardized mortality ratios with reoperative cardiac surgery were highest early and late in a surgeon's career and lowest in mid career. As surgeons gain experience, outcomes improve through the first two career decades, then stabilize in the third decade before declining in the fourth decade.**

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Studies in select surgical subspecialties demonstrate that experience drives technical competence and decision-making capacity for young surgeons, whereas aging plays a role in deterioration of capabilities for senior surgeons.[1-7] The purpose of the current investigation was to determine the impact of surgical experience on outcomes after reoperative cardiac surgery. Reoperative cardiac surgery was selected because it represents a subset of procedures that is associated with increased complexity compared with primary index cases. The objectives were to define patient-related risk factors that impact survival, then to determine the impact of surgeon-specific factors on outcomes in complex cardiac surgery. The hypothesis is that surgical experience impacts results including an initial learning curve for young surgeons with a nonlinear relationship demonstrating skill attrition and a decline in outcomes in surgeons of advanced years.

Patients and Methods

During a 33-year period (January 1986 to March 2019), 2314 patients underwent reoperative cardiac surgery that involved coronary artery bypass grafts (CABG) or a valve procedure at Washington University School of Medicine (Barnes-Jewish Hospital). Isolated left ventricular assist device implantation, transplantation, and nonvalvular congenital, Maze, or thoracic aortic procedures were excluded as it was considered that these represented a niche rather than standard cardiac surgical procedure. The series included 34 different surgeons during their first to thirty-ninth year of experience after completing formal cardiac surgical training. Surgeons were on faculty at Washington University an average of 6.5 years. Surgeons performed as many as 868 cases, with five surgeons performing more than 100 cases. The average number of reoperations was 68 per surgeon with a median of 25 cases per surgeon. The 25% and 75%

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Table 1. Cardiac Surgical Procedures Performed in 2314 Patients Undergoing Reoperation

Reoperative Cardiac Surgery	Incidence
Isolated AVR	651 (28)
Isolated CABG	543 (23)
Isolated MVR	447 (19)
Combined CABG and AVR	136 (6)
Combined AVR and MVR	123 (5)
Combined MVR and TVR	92 (4)
Isolated TVR	86 (4)
Combined CABG and MVR	79 (3)
Isolated pulmonary valve replacement	76 (3)
Various other combinations	81 (4)

Values are n (%).

AVR, aortic valve replacement; CABG, coronary artery bypass graft surgery; MVR, mitral valve repair or replacement; TVR, tricuspid valve repair or replacement.

percentile were 7 and 53 cases, respectively. They included only reoperations performed at Barnes-Jewish Hospital and did not include reoperations that surgeons performed at other hospitals not in The Society of Thoracic Surgeons (STS) Database (for example, St Louis Children's Hospital).

Previous cardiac operations included isolated CABG in 1042 (45%), isolated valve procedures in 993 (43%), combined CABG and valve procedures in 238 (10%), isolated ascending aortic procedures in 16 (0.7%), and isolated nonvalvular congenital or Maze procedures in 25 (1.1%).

Of the 2314 patients undergoing reoperative cardiac surgery, 543 (23%) underwent isolated CABG, 1527 (66%) underwent valve procedures, and 244 (11%) underwent combined CABG and valve procedures. The most common reoperative procedures were isolated redo aortic valve replacement (28%), isolated redo CABG (23%), and isolated redo mitral valve repair or replacement (19%; Table 1). Concomitant procedures included ascending thoracic aortic procedures in 124 patients (5%), Maze procedure in 90 (4%), left ventricular aneurysm repair in 25 (1%), and ventricular septal defect repair in 11 (0.5%).

Calculation of Predicted Risk of Operative Mortality

Operative mortality included any death that occurred during the initial hospitalization or within 30 days of operation for discharged patients. Only 71% of patients had procedures performed that were applicable for STS predicted risk of mortality analysis. Therefore, predicted surgical risk was determined with a predictive probability formula developed using the current dataset. Univariate analysis was used to identify potential risk factors for multivariate logistic analysis. Multivariate logistic analysis (stepwise backward regression) then identified risk factors that were significant, independent predictors of operative mortality. An operative mortality risk prediction model was created using the regression coefficients of the multivariate logistic regression analysis to determine the predictive probability (*PP*) of death:

$$pp = \frac{\exp\,(a + b_1 \times x_1 + b_2 \times x_2 + \ldots b_n \times x_n)}{1 + \exp\,(a + b_1 \times x_1 + b_2 \times x_2 + \ldots b_n \times x_n)}$$

where x_1 through x_n are the variables identified as independent risk factors, b_1 through b_n are the corresponding regression coefficients, and a is the constant. Receiver-operating characteristics curve analysis and area under the curve were used to assess the accuracy of the resulting predictive probability equation.

Standardized mortality ratio (SMR) is the ratio of observed to expected (O:E) operative mortality and was calculated for each year of post-training surgical experience from year one to year 39. One "surgeon-year" represents an individual surgeon's experience during each post-training year they were on the faculty. In total there were 223 surgeon-years for analysis.

Risk-Adjusted Cumulative Sum Analysis

Risk-adjusted cumulative sum (RA-CUSUM) and change-point analysis was performed. Recently, CUSUM has been used to monitor development of proficiency and maintenance of quality in surgical procedures.[7] The RA-CUSUM adjusts for case mix by accounting for individual patient risk factors. The O:E mortality ratio for each reoperation was calculated using the multivariate regression model described above. In graphic representation, a RA-CUSUM curve that moves upward represents a failure, with O:E ratio greater than unity. A curve that moves downward signifies success, with O:E ratio less than unity. The RA-CUSUM curve thus plots successes and failures over time with incremental case experience as a proficiency gain curve.

Change-point analysis identified case numbers at which there was a sustained improvement in outcomes (downward spike, where outcomes change from worse to better than expected) or a sustained deterioration in outcomes (upward spike, where outcomes changed from better to worse than expected). Change points were used to categorize surgeon experience into logical, distinct career phases. The SMR at each career phase was compared using Fisher's exact test with *P* values reporting significant differences in O:E mortality.

Continuous data are reported as mean $\pm$ 1 SD and were compared between groups by analysis of variance. Clinically important ratios are reported with 95% confidence interval (CI) and are compared between groups with χ^2 test. Odds ratios (OR) are reported with 95% CI, and regression coefficients for continuous variables are reported with standard error of the mean (SEM). Expected mortality is presented with SEM, and observed mortality and SMR are presented with 95% CI All statistical analyses were performed using Systat 10.2 or SigmaPlot 12.5 (Systat Software, San Jose, CA). The study was approved by the Washington University School of Medicine Institutional Review Board.

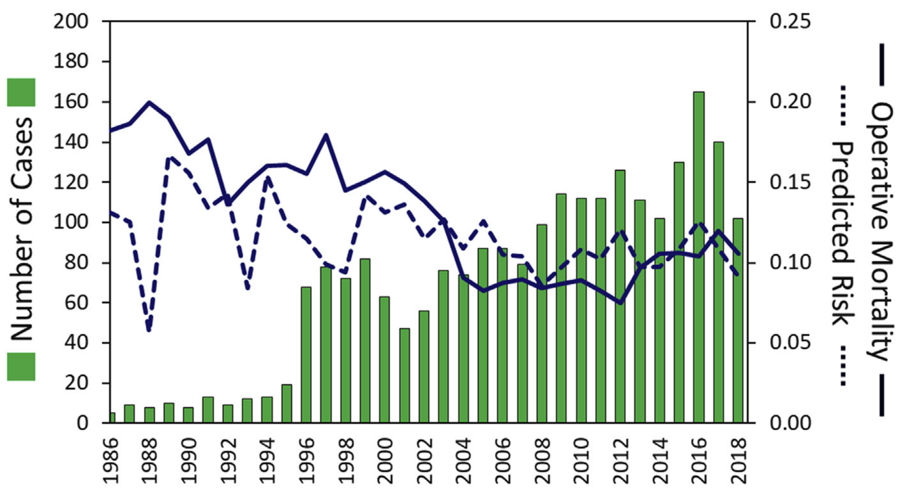

Figure 1. Number of reoperative cardiac surgery procedures (bars), operative mortality (solid line), and predicted risk (broken line) at Washington University School of Medicine (Barnes-Jewish Hospital) from 1986 to 2019.

Results

Reoperative cardiac surgery was uncommon before 1996, then became increasingly more common with a fall in operative mortality and predicted risk (described below) in the second half of the series so that SMR did not change substantially over time (Figure 1). Operative mortality was 11% ± 1.3% overall (255 of 2134 patients). Postoperative complications included reoperation for bleeding (151 patients, 6.5%), myocardial infarction (21, 0.9%), cerebral vascular accident (69, 3%), prolonged ventilation (725, 31.3%), acute renal failure requiring dialysis (133, 5.7%), deep sternal infection (16, 0.7%), and mechanical circulatory support for shock (22, 1.0%).

Table 2 summarizes the incidence of 35 clinically important variables in operative survivors versus nonsurvivors. Univariate analysis yielded 24 significant variables associated with operative mortality for inclusion in multivariate analysis. Ten factors were identified with multivariate analysis to be independent predictors of operative mortality (Table 3). In decreasing order of impact, independent risk factors included preoperative shock, chronic renal disease, combined CABG and valve procedure, age 80 years or more, New York Heart Association class III or IV, tricuspid valve procedure, more than one previous cardiac surgical procedure, mitral valve procedure, history of myocardial infarction, and peripheral vascular disease. The resulting risk prediction model for operative mortality was analyzed using the receiver-operating characteristics curve with area under the curve = 0.7426 ($P < .001$; Figure 2). The predicted risk of mortality ranged from 2.4% to 81.2% with an average predicted risk for the entire cohort of 11% ± 0.2%.

Figure 3 is the RA-CUSUM curve for progressive reoperative cardiac surgical cases for all 34 surgeons based on years of experience after completion of their cardiac surgery training. Change-point analysis identified five distinct career phases: 0 to 4 years (55 surgeon-years, 331 patients), 5 to 8 years (44 surgeon-years, 427 patients), 9 to 17 years (72 surgeon-years, 834 patients), 18 to 28 years (32 surgeon-years, 558 patients), and 29 to 39 years (20 surgeon-years, 164 patients). Table 4 demonstrates SMR versus years in practice based on RA-CUSUM defined change points. The SMR was near unity with 5 to 8 years and 18 to 28 years of experience (0.95 and 1.05, respectively). The SMR was lowest mid career with 9 to 17 years of experience (0.78, $P = .03$). In the youngest experience group (0 to 4 years), observed and expected mortality rates were both highest, and the SMR was elevated at 1.29 (95% CI, 0.99 to 1.70), which approached statistical significance ($P = .059$). In the oldest experience group (29 to 39 years), expected mortality was low compared with most other groups but observed mortality increased, yielding a significantly elevated SMR at 1.53 ($P = .032$). Figure 4 demonstrates the fall in SMR during mid career with a rise in the later stages.

Comment

Reoperative cardiac surgery is more complex and can be more time consuming when compared with a primary intervention. Reoperations require considerable physical stamina and mental acuity, and outcomes can be directly related to surgical skill, caseload experience, and the knowledge base of the surgeon. Checklists and a "huddle" may decrease failure to rescue from intraoperative adverse events, which can still occur despite thorough preoperative planning and meticulous surgical technique.[8,9] The current study of high-risk procedures was performed to identifying groups of surgeons who might benefit most from performance improvement efforts, for example, through adoption of a systematic protocol-driven approach for reoperation.[9-11]

Surgical Learning Curve

The Harvard group determined that learning curves are present for reduction mammaplasty, a procedure that is labor intensive but of low complexity.[4] In their series, plastic surgeons did not achieve a state of maximum efficiency until 12 years beyond training. In general surgery, Prystowsky[2] demonstrated a learning curve for operations of high complexity but not low complexity.

Table 2. Incidence of Clinically Important Variables in Operative Survivors Versus Nonsurvivors

Variable	Alive	Dead	*P* Value
Number of patients	2059	255	...
Age, y	61 ± 15	66 ± 14	<.001
Female	37	44	.04
Smoking history	58	58	.94
Family history of CAD	25	23	.65
Diabetes mellitus	30	31	.64
Hypertension	70	75	.14
Hypercholesterolemia	68	69	.87
Cerebrovascular accident	13	18	.05
Chronic pulmonary disease	27	33	.03
Chronic renal disease	9	29	<.001
History of endocarditis	15	17	.47
Active endocarditis	6	10	.03
Chronic pulmonary hypertension	31	47	<.001
Peripheral vascular disease	21	30	.002
Prior myocardial infarction	38	50	<.001
Prior CABG	54	63	.01
Congestive heart failure	68	78	.001
Left ventricular ejection fraction	0.48 ± 0.16	0.45 ± 0.16	.007
NYHA class III or IV	66	84	<.001
Body surface area	2 ± 0.3	1.9 ± 0.3	.02
More than one reoperation	19	26	.006
History of atrial fibrillation	31	39	.03
Urgent or emergent status	17	31	<.001
Preoperative shock	3	15	<.001
Preoperative IABP	2	8	<.001
Median sternotomy	89	89	.96
Component procedures			
CABG	38	33	.13
Aortic valve replacement	41	43	.73
Mitral valve procedure	32	48	<.001
Tricuspid valve procedure	9	17	<.001
Pulmonary valve replacement	4	0	.001
CABG with any valve procedure	9	25	<.001
Concomitant Maze procedure	4	4	.89
Concomitant aortic procedure	5	8	.03
Concomitant LVA/VSD	2	2	.78

Values are percentage or mean ± SD, unless otherwise noted. Groups were compared using analysis of variance or χ^2 test as appropriate.

CABG, coronary artery bypass graft surgery; CAD, coronary artery disease; IABP, intraaortic balloon pump; LVA, left ventricular aneurysm; NYHA, New York Heart Association; VSD, ventricular septal defect.

Young surgeons (less than 5 years since board certification) had substantially worse outcomes with complex alimentary tract procedures compared with midcareer surgeons; morbidity increased by 12% and mortality by 30%. For low-complexity operations, there was no difference. For senior surgeons (30 years beyond certification), there was also a tendency for mortality to rise in high-complexity operations by 13% compared with those in mid career, but the difference did not reach statistical significance. With low-complexity operations, senior surgeons maintained equivalent outcomes.

The Northern England Cardiac Surgery Consortium reported a progressive decrease in operative mortality during the first 4 years after appointment to a cardiac surgery consultant position.[1] Operative mortality fell from 2.2% to 1.2% ($P = .049$) for first-time isolated CABG. This improvement was independent of case mix and patient comorbidities. In the current report, evidence of a learning curve similarly appears during the first 4 years of practice with outcomes improving, then ultimately stabilizing throughout the midcareer phase. As surgeons gained experience, outcomes improved through the first 2

Table 3. Ten Independent Risk Factors for Operative Mortality Identified With Multivariate Logistic Regression Analysis

Risk Factor	OR (95% CI)	Regression Coefficient	SE	*P* Value
Preoperative shock	5.5 (3.5-8.9)	1.713	0.241	<.001
Chronic renal disease	3.7 (2.6-6.7)	1.059	0.170	<.001
Combined CABG/valve	2.2 (1.5-3.2)	0.802	0.190	<.001
Age more than 80 years	2.1 (1.4-3.2)	0.738	0.221	.001
NYHA class III or IV	2.0 (1.4-2.9)	0.693	0.186	<.001
Tricuspid valve procedure	1.8 (1.2-2.7)	0.582	0.203	.004
>1 previous cardiac operation	1.7 (1.2-2.4)	0.531	0.167	.001
Mitral valve procedure	1.5 (1.2-2.0)	0.429	0.145	.003
History of myocardial infarction	1.5 (1.1-2.0)	0.386	0.147	.009
Peripheral vascular disease	1.4 (1.0-1.9)	0.324	0.163	.046
Constant		−3.724	0.201	<.001

CABG, coronary artery bypass graft surgery; CI, confidence interval; NYHA, New York Heart Association; OR, odds ratio.

career decades, then stabilized in the third decade before declining in the fourth decade.

The Brigham group[5] examined the influence of experience and surgical learning in cardiac surgery, reviewing 6591 patients, the majority of whom underwent a primary operation. The study period spanned only 10 years, unlike the current report which included numerous surgeons passing through several career phases during the 33-year study period. Therefore, the Brigham group essentially compared three distinct groups of surgeons—early career (0 to 8 years), mid career (11 to 21 years), and late career (more than 30 years)—with very little crossover between groups. They reported better outcomes and improved operative efficiency during valve procedures in the late career group. That was in contrast to CABG, which had similar outcomes regardless of career phase. Because crossover between career phases was limited during the brief study period, conclusions could not be

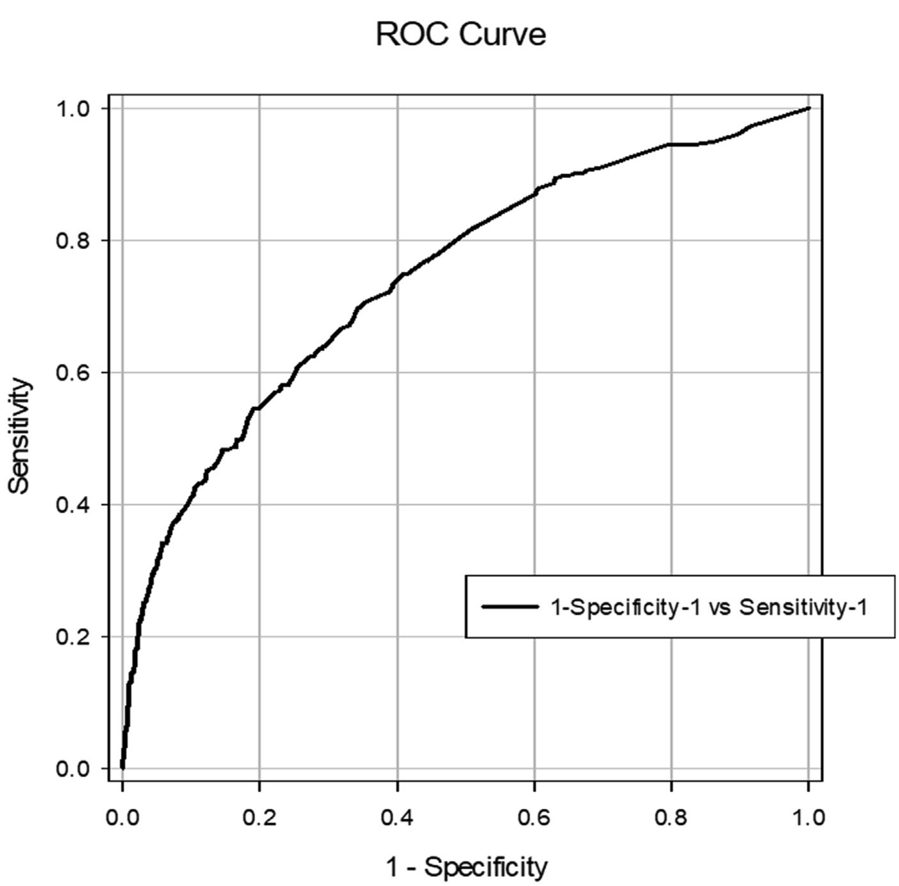

Figure 2. Receiver-operating characteristics (ROC) curve of the relationship between predictive probability of death and actual operative mortality.

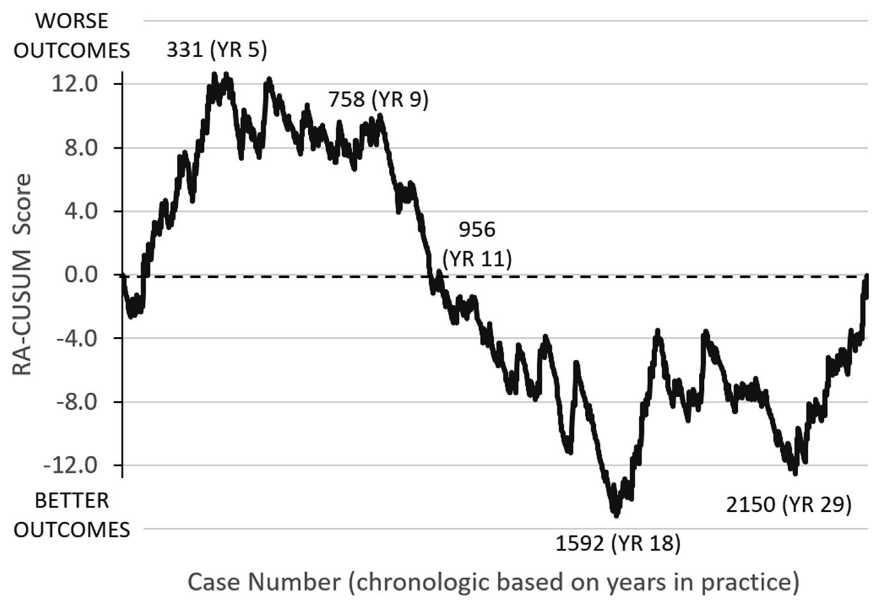

Figure 3. Risk-adjusted cumulative sum (RA-CUSUM) curve for reoperative cardiac surgery, all 34 surgeons included, based on years (YR) of experience after cardiac surgery training. An increment (upward spike) represents a failure or worse than expected outcome, whereas a decrement (downward spike) signifies a success or better than expected outcome.

made about the course of an individual career path. Other studies report that the learning curve for CABG efficiency appears relatively flat.[3,12,13] At teaching hospitals, efficiency has more to do with the cumulative team experience than the individual experience of either the surgeon or surgical trainee.[12] The modest learning curve for CABG is potentially a consequence of the relatively large number of CABG procedures required by the American Board of Thoracic Surgery during training compared with the limited experience most residents obtain in reoperative cardiac surgery.

Simulators have been developed to facilitate routine cardiothoracic task training,[14] but reoperative cardiac surgery involves unpredictability that cannot be easily replicated in models. Gone are the days when an attending could leave residents on their own to muddle through a difficult case for educational purposes. There is no room for trial and error training, only “continually supervised, corrected perfection.”[15] Early career surgeons should consider adoption of a protocol-driven approach to cardiac reoperation[9-11] and request the assistance of a senior partner when possible to review the operative plan and assist with complex technical aspects of the case.

Skill Attrition and the Aging Surgeon

Anderson and colleagues[6] queried the STS Congenital Heart Surgery Database to examine the impact of surgeon seniority on outcomes in pediatric patients. They examined 206 surgeons at 91 centers performing 62,851 index operations over a 5-year period. This study defined early career phase as less than 15 years after graduation from medical school, generally corresponding to the 1- to 4-year post training group in the current report. Mid career was defined as 15 to 24 years, senior surgeons as 25 to 34 years, and very senior surgeons as 35 years after medical school. Their data showed that very senior surgeons, generally greater than 60 years of age, had a significantly higher hazard ratio of major morbidity or mortality at 1.24 (95% CI, 1.03 to 1.49; $P = .022$) than the early career surgeons after adjusting for patient characteristics. They concluded that for congenital heart surgeons at the tail end of their career, performance appears to suffer. They did not specifically identify a learning curve in the younger surgeons, but they did note a significantly lower acuity in the patients on whom the younger surgeons operated. The more junior surgeons performed fewer high risk operations than senior surgeons and fewer reoperations.

Table 4. Observed Mortality, Expected Mortality, and Standardized Mortality Ratio Versus Years in Practice for Five Career Stages

Years inPractice	Surgeon-Years	Cases	Observed Mortality (%)	Expected Mortality (%)	SMR (95% CI)	*P* Value
0-4	55	331	15.7 ± 4.1	12.1 ± 0.6	1.29 (0.99-1.70)	.059
5-8	44	427	11 ± 3.1	11.6 ± 0.6	0.95 (0.71-1.26)	.724
9-17	72	834	8.9 ± 2	11.3 ± 0.4	0.78 (0.62-0.98)	.034
18-28	32	558	10.2 ± 2.6	9.8 ± 0.4	1.05 (0.81-1.36)	.735
≥29	20	164	15.2 ± 5.7	10 ± 0.7	1.53 (1.03-2.26)	.032

The *P* values compare observed-to-expected mortality with χ^2 test and Fisher’s exact test. Observed mortality and standardized mortality ratio (SMR) are reported with 95% confidence interval (CI), and expected mortality is presented with standard error of the mean.

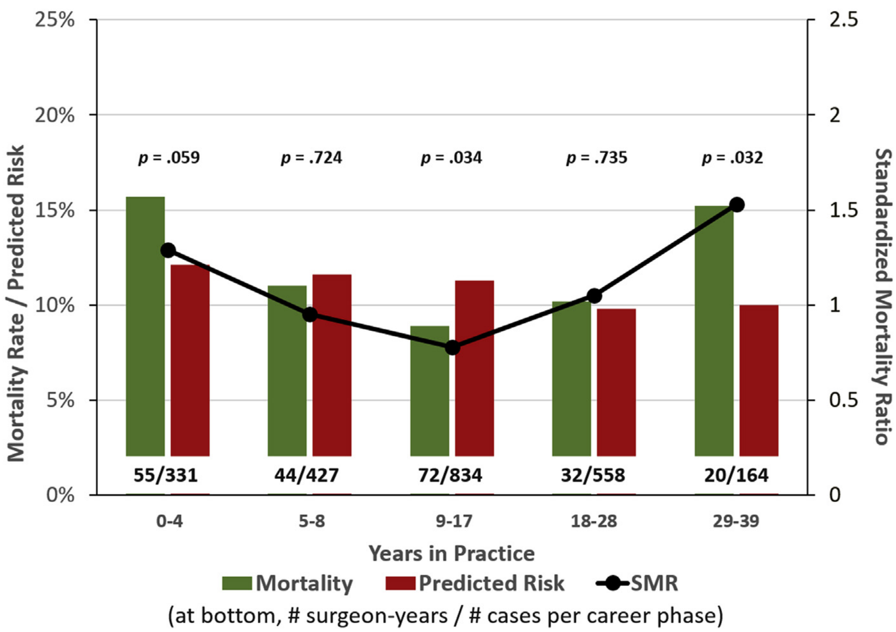

Figure 4. *Observed mortality rate (green bars), expected mortality (predicted risk) rate (red bars), and standardized mortality ratio (black line) versus years in practice for five career stages defined using risk-adjusted cumulative sum change-point analysis: 0 to 4 years, 5 to 8 years, 9 to 17 years, 18 to 28 years, and 29 to 39 years. The P values compare observed-to-expected mortality with χ^2 test. At the bottom of the columns is displayed the number of surgeon-years in each career phase and the number of cases in each career phase.*

Waljee and Greenfield[16] summarized studies demonstrating a decline of motor skills and dexterity with age including precision, accuracy, and stamina. These deficiencies can be overcome by older persons, but doing so requires extended deliberate practice. Age does not impair memory encoding such that motor memory is preserved; however, cognitive decline occurs after age 65 years, and integration of motor and cognitive tasks can suffer. When older adults face a cognitive challenge, performance of a subsequent motor task can be unpredictable. In a muscle memory operation with limited variability (ie, a straightforward first-time isolated procedure), consistent results can be expected. Once variability is introduced, as is often the case in cardiac reoperations, outcomes become less predictable. Reoperative cardiac surgery presents many potential unknowns such that muscle memory plays a lesser role in ensuring consistent outcomes.

Maintaining procedural volumes can counter age-related deterioration in outcomes.[3] A recent study examining surgical learning during thoracoscopic lobectomy identified a distinct learning curve with new technologies, but more importantly identified that maintenance of proficiency is not ensured even after one has passed through the initial learning curve.[7] Complex thoracic surgery is not “just like riding a bike” and reoperative cardiac surgery represents the extreme of difficult surgeries. Surgeons at all levels need to maintain an adequate caseload. In the current report, midcareer surgeons performed more reoperations than those at the ends of the spectrum. A survey of senior surgeons reported that the largest decline in operative activity occurs between 60 and 70 years of age, consistent with the beginning of the most senior career phase in the present study.[17] During this time, rather than retire, most surgeons continued to operate but at lower and lower caseload levels. This approach may not be optimal. Surgeons maintaining caseloads for high complexity cases until retirement, or who shift their practice to lower complexity cases, may best support efforts to improve the quality of patient care.

The findings of the current report should not be used to determine who should or should not perform a complex cardiac surgery reoperation based on age, whether young or old. Procedural volume, practice setting, and team dynamics play a critical role. These results instead should provide insight into cognitive and physical limitations in older surgeons and the need for additional exposure in younger surgeons to prompt self-assessment and practice-based learning. In his Presidential Address to the Southern Thoracic Surgical Association, Dr David Jones spoke of the quest to achieve expertise and “bend the curve.”[18] Our findings clearly demonstrate that with experience, the curve will bend. Our data support the hypothesis that a “sweet spot” exists in a surgeon’s career during which clinical outcomes after reoperative cardiac surgery are at their best, but with awareness and intervention, hopefully we can flatten the curve at the bookends of our career.

Study Limitations

It would have been interesting to evaluate career surgical volume in the analysis, but it was not possible for a couple of reasons: (1) some surgeons practiced at other hospitals (St Louis Children’s Hospital, for example) that were not included in our STS database set, and so the total number of reoperations for these surgeons was not available; and (2) many surgeons joined the faculty at Washington University mid career, and their prior experience at other institutions was not available. All cases were recorded based on only the attending of record; we did not have consistent records of the first assistant. Therefore, we could not evaluate the impact of two-attending versus one-attending operations, nor the impact of attending surgeon versus resident as primary operator.

In many cases, the early career or late career surgeon may very well be the most appropriate member of the team to tackle a complex reoperation. To mitigate some of the difficulty in these high-risk challenging cases, it is important for the surgeon to adopt a protocol-driven approach to ensure the highest quality care. Interventions we plan to consider include the following: (1) thorough preoperative planning with the operative team using checklists or the preoperative "huddle" to minimize surprises and develop contingency plans; (2) perform the most complex reoperative cases earlier in the day when well rested and in ideal physical condition to proceed; (3) enlist the assistance of other team members, whether an attending colleague or high-level trainee, to lighten the physical and cognitive strain that can accompany a complex reoperation; (4) consider teaming an early career surgeon with a late career surgeon for complex reoperations as such an interaction could serve both surgeons well, including mentorship for the young surgeon and physical and mental support for the senior surgeon; and finally, (5) even under the best of circumstances and with the most thorough of planning, intraoperative adverse events will occur during complex reoperations. With adequate team planning and surgeon preparation, failure to rescue can remain low for surgeons at any phase of their career.

Conclusion

Reoperative cardiac surgery is technically more demanding and associated with increased risk compared with primary cardiac operations. The current data support the hypothesis that a period exists in a surgeon's mid career during which clinical outcomes after reoperative cardiac surgery are at their best. During the early phase and most senior phase of a surgeon's career, technical proficiency, physical stamina, and cognitive knowledge may not be at their peak.

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