A CROSS-SPECIALTY ANALYSIS OF SURGICAL LEARNING CURVES

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A CROSS-SPECIALTY ANALYSIS OF SURGICAL LEARNING CURVES

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ABSTRACT

Objectives: to evaluate the learning curves of three high-volume procedures, from distinct surgical specialties.

Setting: Tertiary care academic hospital.

Participants: A prospectively collected database comprising all medical records of patients undergoing isolated coronary artery bypass grafting (CABG), total knee replacement (TKR) and bilateral reduction mammoplasty (BRM) at the Brigham and Women's Hospital, U.S.A, 1996-2010. Multivariate generalized estimating equation (GEE) regression models were used to adjust for patient risk and clustering of procedures by surgeon.

Primary and secondary outcome measures: operative efficiency.

Results: A total of 1052 BRMs, 3254 CABGs and 3325 TKRs performed by 30 surgeons were analysed. Median number of procedures per surgeon was 61 (range 11-502), 290 (52-973) and 99 (10-1871) for BRM, CABG and TKR respectively. Mean operative times were 134.4 (standard deviation 34.5), 180.9 (62.3) and 101.9 (30.3) minutes respectively. For each procedure, attending surgeon experience was associated with significant reductions in operative time (P<0.05). After 15 years of experience, BRM operative time decreased by 69.8 minutes (38.3%), CABG operative time decreased by 17.5 minutes (7.8%) and TKR operative time decreased by 94.4 minutes (48.4%).

Conclusions: Common trends in surgical learning exist. Dependent upon the procedure, experience can serve as a powerful driver of improvement or have clinically insignificant impacts on operative time.

Trial registration: N/A

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Key Words: Learning curve, performance curve, operative efficiency, CABG, total knee replacement, reduction mammoplasty

Article focus

- Surgical experience is known to influence performance. We performed a comparative study evaluating the learning curves of three high-volume procedures.

Key messages

- This study quantitatively characterised the learning curves of three procedures from distinct surgical specialties – total knee replacement, bilateral reduction mammoplasty and isolated coronary artery bypass grafting.
- Common trends in surgical learning were found to exist. Dependent upon the procedure, experience can serve as a powerful driver of improvement or have clinically insignificant impacts on operative time.
- In contrast to the notion that efficiency is optimised within a fairly narrow temporal window following the start of clinical practice, our data suggest that operative learning curves, for some procedures, exhibit ongoing improvement in efficiency over the course of a surgeon's career, with time courses much longer than previously anticipated.

Strengths and limitations of this study

- Use of high-granularity data on over 7000 procedures, performed by 30 surgeons; robust statistical demonstration of the effect of experience on operative efficiency.
- Single centre, retrospective, and focused on operative time, which although has clear relevance to operative efficiency and financial costs, is not a clear patient-centred outcome.

INTRODUCTION

Performance measurement and the application of quality, efficiency and safety metrics in surgery has dramatically expanded over the past two decades. This has met with variable compliance and success. The operating room (OR) represents a high-risk environment, requiring the coordination of technology, competence and resources under time pressure by the operating team [1, 2]. When combined with the technical and dexterous nature of surgery, it is apparent that several factors must be considered and accounted for to make accurate, equitable and comparable measurements of performance between surgeons. One of these factors is the learning curve inherent to operative procedures [3, 4, 5, 6, 7, 8].

Until recently, studies have lacked adequate data volume and resolution to gain an appropriate understanding of procedural dynamics, or robustly identify suitable performance metrics. Work thus far has predominantly focused on surgery at the institutional or departmental level, rather than that of the individual surgeon. Furthermore, no studies to date have compared learning curves across different surgical specialties using statistically uniform methods [8].

We performed a cross-specialty, comparative study evaluating the learning curves of three high-volume and well-defined procedures: bilateral reduction mammoplasty (BRM), isolated coronary artery bypass grafting (CABG) and total knee replacement (TKR). Our intent was to define commonalities and discrepancies in the learning curves of these procedures, and thereby identify overarching themes that may inform future surgical performance improvement efforts.

METHODS

Design and Population

Data for all CABG, TKR and BRM procedures performed at Brigham and Women's Hospital (BWH), 2001-2010, 1996-2009 and 1995-2007 respectively, were culled from a combination of electronic medical records, an electronic operative time tracking application, and physician employee databases. The datasets were filtered to exclude CABGs that were accompanied by concomitant procedures (e.g., valve surgery, MAZE, etc.); erroneously coded procedures including partial knee replacements, combined procedures and bilateral TKR procedures; gynaecomastia, resections and partial/total mastectomies; and incomplete or incorrect data entries. Datasets were subsequently filtered to only include surgeons who conducted more than 10 procedures annually, focusing on the first twenty years of the learning curve.

For CABG, the primary dependent variable was operative time defined as the sum of cardiopulmonary bypass time (CPB) and cross clamp time. For TKR and BRM, operative time was defined as the time elapsed from skin incision to skin closure. The operative experience of the attending surgeon was calculated as the difference between the date of the procedure and that of the surgeon's completion of training. This study was performed under Institutional Review Board approval (protocol 2006p000586).

Statistical Analysis

Surgical Learning Curves

The characteristics of patients and surgeons were described using absolute frequencies with percentages for categorical variables. The mean values with standard deviations and median values with minimum-maximum intervals were calculated for continuous variables.

The expected learning curve of surgeons over time was generated based on a multivariate generalized estimating equations (GEE) regression model. A number of possible shapes of learning curves were tested in order to obtain the best fitting [9]. Outcomes were adjusted for clustering of patients by surgeon, as well as patient case-mix factors (for CABG: patient age, sex, preoperative cardiogenic shock, diabetes mellitus and preoperative congestive heart failure; for TKR: patient age, sex and co-morbidities including coronary artery disease, chronic obstructive pulmonary disease, diabetes mellitus, hypertension, obesity and smoking; for BRM: volume of breast reduction) [9]. Selection of covariates for generation of case-mix models was achieved using the approach described by Collett [10]. Model estimates were obtained using the GENMOD procedures in SAS™ 9.2 (SAS Institute Inc., Cary, NC, USA). The expected reductions in operative time associated with attending experience were plotted. All tests were two-tailed, and *p*-values <0.05 were considered significant.

RESULTS

Surgeon and cohort characteristics for each procedure are listed in Tables 1 and 2. Figure 1 displays the learning curve of each of the procedures.

A total of 1052 BRMs were completed by 8 surgeons. Mean attending experience was 11.3 ± 4.5 years, with a median case volume of 61 (range: 11-502). Mean operative time was 134.4 ± 34.5 minutes. Multivariate regression showed breast reduction volume to be the only case-mix factor to have a significant effect on operative time. After adjusting for patient characteristics and clustering, we found a significant association between operative time and attending surgeon experience entered both as a linear (P=0.0002) and a quadratic (P=0.0427) term in the model. Five, ten and fifteen years of experience were associated with 33.74, 57.02 and 69.82 minute reductions in operative time respectively, equating to 18.51%, 31.28% and 38.30% reductions (Table 3).

A total of 3254 CABGs were completed by 9 surgeons. Mean attending experience was 9.7 ± 5.9 years, with a median case volume of 290 (range: 52-973). Mean operative time was 180.9 ± 62.3 minutes. Multivariate regression showed the following case-mix factors to have a significant effect on operative time: patient age, sex, preoperative cardiogenic shock, diabetes mellitus and preoperative congestive heart failure. After adjusting for patient characteristics and clustering, we found a significant association between operative time and attending surgeon experience entered as a logarithmic term (P=0.0374) in the model. Five, ten and fifteen years of experience were associated with 5.85, 11.69 and 17.54 minute reductions in operative time respectively, equating to 2.61%, 5.22% and 7.83% reductions (Table 3).

Surgical Learning Curves

A total of 3325 TKRs were completed by 13 surgeons. Mean attending experience was 14.5 ± 3.8 years, with a median case volume of 99 (range: 10-1871). Mean operative time was 101.9 ± 30.3 minutes. Multivariate regression showed the following case-mix factors to have a significant effect on operative time: patient age, sex and co-morbidities including coronary artery disease, chronic obstructive pulmonary disease, diabetes mellitus, hypertension, obesity and smoking. After adjusting for patient characteristics and clustering, we found a significant association between operative time and attending surgeon experience entered both as a linear (P<0.0001) and a quadratic (P=0.0002) term in the model. Five, ten and fifteen years of experience were associated with 38.20, 69.68 and 94.41 minute reductions in operative time respectively, equating to 19.60%, 35.75% and 48.44% reductions (Table 3).

DISCUSSION

We performed a cross-specialty evaluation of learning curves in surgery, investigating over 7,000 procedures performed by 30 attending surgeons. By comparing these learning curves using statistically uniform data and techniques, our study permits identification of important commonalities and differentiations, yielding several important findings:

First, in contrast to the notion that efficiency is optimised within a fairly narrow temporal window following the start of clinical practice, our data suggest that operative learning curves, for some procedures, exhibit ongoing improvement in efficiency over the course of a surgeon's career, with time courses much longer than previously anticipated. This emphasizes the necessity to draw equitable comparisons between surgeons at similar stages of the learning curve [11, 12], and supports proposals for continual monitoring, training and behavioural interventions aiming to accelerate operative maturation [13].

Second, our results demonstrate the different learning curve dynamics that exist between procedures. BRM is typified by an initial phase of variability, followed by a period of rapid improvement, followed by a relative plateau phase. TKR and CABG, on the other hand, demonstrate a more linear improvement over time. Such findings suggest that certain procedures may demonstrate characteristic learning curves, with some achieving maturation more rapidly than others. The factors contributing to these characteristics should be the subject of further investigation.

Third, the magnitude of improvements in efficiency over time varies from procedure to procedure. In some cases, efficiency is markedly augmented with increasing surgeon experience (BRM and TKR); in others, however, the improvement is substantially more marginal, and possibly clinically insignificant (CABG; <10% reduction after fifteen years of experience). This observation may be because cardiothoracic fellows begin their training as proficient and highly competent general surgery graduates. As demonstrated by previous studies, this may result in attendings achieving a significant portion of their maturation as CABG surgeons during their cardiothoracic fellowship [14, 15, 16], diminishing the impact of subsequent increases in experience. Superimposed on this is the possibility that plastic and orthopaedic surgeons may learn a broader range of procedures during their training than cardiothoracic surgeons, precluding as much experience to be gained in a given operative technique – a difference of breadth and depth. This observation suggests that interventions aiming to accelerate surgical experience acquisition, such as simulation training, may be particularly effective for enhancing efficiency in TKR and BRM, but possibly less so in CABG, given the differential impact of individual surgeon experience across these procedures.

In addition to this, procedural learning curves were found to have differential sensitivities to case-mix factors. BRM was only affected by breast reduction volume; in contrast, the TKR learning curve was found to be influenced by a variety of patient-factors including age, sex and co-morbidities. This differential is no doubt due, at least in part, to varying tolerances on the part of surgeons in each of the highlighted specialties to operate on patients with marginal health status; this must be taken into consideration when making cross-procedural comparisons.

Importantly, the development of experience-based learning curves, like those elucidated in this study, has the potential to inform efforts to prospectively monitor individual surgical performance metrics on an ongoing basis. Through the application of iterative quality improvement systems such as statistical process control (SPC), the depicted learning curves could be utilised as a baseline against which to chart the progress of surgical personnel – whether to meet administrative or educational goals [17, 18]. Such methodologies are designed to first identify and then address unwarranted variation in clinical processes, which generally leads to substantial improvements in efficiency, safety and quality. While initially conceived for the manufacturing industry, they have recently been recognised as having increasing relevance to the healthcare sphere [19, 20]. Compared to more traditional approaches of quality control, they offer a more accurate means of assessing performance and guiding improvement initiatives, particularly when they are, as in the case of the data presented here, tailored to a specific operative procedure [11, 12].

Implementation of SPC offers several potential benefits. Through improvement of surgical performance, these efforts have the potential to simultaneously improve surgical efficiency, safety, quality and cost at both the individual and institutional levels. In the context of training, mapping of performance throughout a surgeon's career will permit the evolution of young trainees to be monitored, giving rise to appraisals based upon performance rather than career chronology alone, potentially ensuring progression only upon acquisition of sufficient expertise [3, 11, 12, 21]. Deconstruction of the performance curve and comparison of curves between high and low performers will permit the elements contributing to training to be dissected. By doing so, the mechanics of surgical learning will be better understood, providing methods by which the learning curve can be accelerated. SPC methodology also presents a means of accurately assessing the efficacy of new training tools or simulation programs at the individual level, both rapidly and sensitively. Finally, this methodology may have the capacity to identify deteriorations occurring towards the end of a surgeon's career, serving as a safety monitor, and supplementing the introduction of continuing education programs [4, 22].

These implications, however, must be considered in the context of this study's limitations:

1) Our focus on operative efficiency as an outcome for CABG, TKR and BRM did not explicitly incorporate considerations related to surgical safety such as complication rates. However, in a variety of work both within surgery and outside, time of task completion has been used as a robust indicator of learning and outcome [3, 23, 24, 25, 26, 27]. Studies have indicated that faster completion of the TKR procedure is associated with better outcomes [28]. Further, operative times in CABG are closely linked with patient outcome; specifically, elevated CPB times are associated with increased risks of stroke and renal failure [29].
2) We performed a retrospective investigation at a single academic medical centre. This approach, however, removed any Hawthorne effect with regard to efficiency assessment. We also did not account for changes in technology or local hospital resources occurring during the retrospective capture of our analysis.
3) Our investigation utilised years of training and/or practice as a proxy for surgical experience, rather than number of cases performed. This limitation is due to our inability to capture procedures performed at other institutions by surgeons in our study cohort. However, years of training and/or practice has been utilised as an acceptable substitute for

surgical experience in prior published studies in the surgical literature [3, 4, 8, 11, 12, 30].

This study quantitatively characterised the learning curves of three procedures from distinct surgical specialties. We identified common trends in surgical learning and demonstrated that, dependent upon the procedure, surgical experience can serve as a powerful driver of improvement or have clinically insignificant impacts on efficiency. Appreciation of these findings may guide implementation of performance-tracking and quality-improvement strategies in surgery.

Table 1: Overview of study participants

		BRM	CABG	TKR
Surgeon	Attending surgeons (n)	8	9	13
	Mean experience, years (SD)	11.3 (4.5)	9.7 (5.9)	14.5 (3.8)
	Min-Max experience	1-19	1-19	1-19
	Median volume of cases	61	290	99
	Range of cases	11-502	52-973	10-1871
Patients	Total number of cases	1052	3254	3325
	Mean patient age, years (SD)	36.4 (12.4)	65.8 (10.4)	66.0 (11.2)
	Female sex (%)	100	23.7	69.0
	Mean size of breast reduction reduction (SD)	1681.3 (934.4)	-	-
	Coronary artery disease (%)	2.3	100.0	21.4
	Chronic obstructive pulmonary disease (%)	12.9	9.9	6.4
	Diabetes mellitus (%)	5.6	38.0	17.9
	Obesity (%)	33.1	34.9	25.9
	Smoking history (%)	6.6	41.6	15.9
	Cardiac Heart Failure (%)	-	24.2	-
	Preoperative Cardiogenic Shock (%)	-	2.3	-

Table 2: Surgeon and statistical model characteristics

Surgical Procedure	**BRM**	**CABG**	**TKR**
Factors included in patient case-mix adjustment	Breast Reduction Volume	Age, Sex, Preoperative Congestive heart failure, Preoperative cardiogenic shock, Diabetes mellitus	Age, Sex, Coronary artery disease, Chronic obstructive pulmonary disease, Diabetes mellitus, Hypertension, Obesity Smoking
Time period data available	13 years (1/18/1995-12/21/2007)	9 years (05/01/2002-09/30/2010)	14 years (07/28/1999-06/29/2009)
No. surgeons	8	9	13
No. surgeon-years	52	48	123
No. procedures	1052	3254	3325
Median No. procedures per surgeon (min-max)	61 (11-502)	290 (52-973)	99 (10-1871)
Mean operative time (SD)	134.4 (34.5)	180.9 (62.3)	101.9 (30.3)
Model	GEE (clustering and case-mix adjusted; linear and quadratic model used)	GEE (clustering and case-mix adjusted; logarithmic model used)	GEE (clustering and case-mix adjusted; linear and quadratic model used)

Table 3: Learning curve – reductions in operative time with surgical experience

	Change in operative time		
Experience (years)	BRM	CABG	TKR
0	0	0	0
1	-7.5867	-1.169409898	-8.1803
2	-14.7546	-2.338819796	-16.0912
3	-21.5037	-3.508229694	-23.7327
4	-27.834	-4.677639593	-31.1048
5	-33.7455	-5.847049491	-38.2075
6	-39.2382	-7.016459389	-45.0408
7	-44.3121	-8.185869287	-51.6047
8	-48.9672	-9.355279185	-57.8992
9	-53.2035	-10.52468908	-63.9243
10	-57.021	-11.69409898	-69.68
11	-60.4197	-12.86350888	-75.1663
12	-63.3996	-14.03291878	-80.3832
13	-65.9607	-15.20232868	-85.3307
14	-68.103	-16.37173857	-90.0088
15	-69.8265	-17.54114847	-94.4175
16	-71.1312	-18.71055837	-98.5568
17	-72.0171	-19.87996827	-102.4267
18	-72.4842	-21.04937817	-106.0272
19	-72.5325	-22.21878806	-109.3583

CONTRIBUTORSHIP STATEMENT

Author's contributions: study concept and design (AD, DPO, MJC, MM, SL); data collection (MJC, MM) and analysis (AD, SL); manuscript preparation (AD, MJC, MM) and revision (AD, DPO, MJC, MM, SL).

COMPETING INTERESTS

None.

Financial Disclosure and Products Statement

None of the participating authors has a conflicting financial interest related to the work detailed in this manuscript, nor do any of the authors maintain a financial stake in any product, device or drug cited in this report. Ethical and institutional board approval was granted prior to conducting this study. Information on data used in this report is available upon request.

DATA SHARING

No additional data available.

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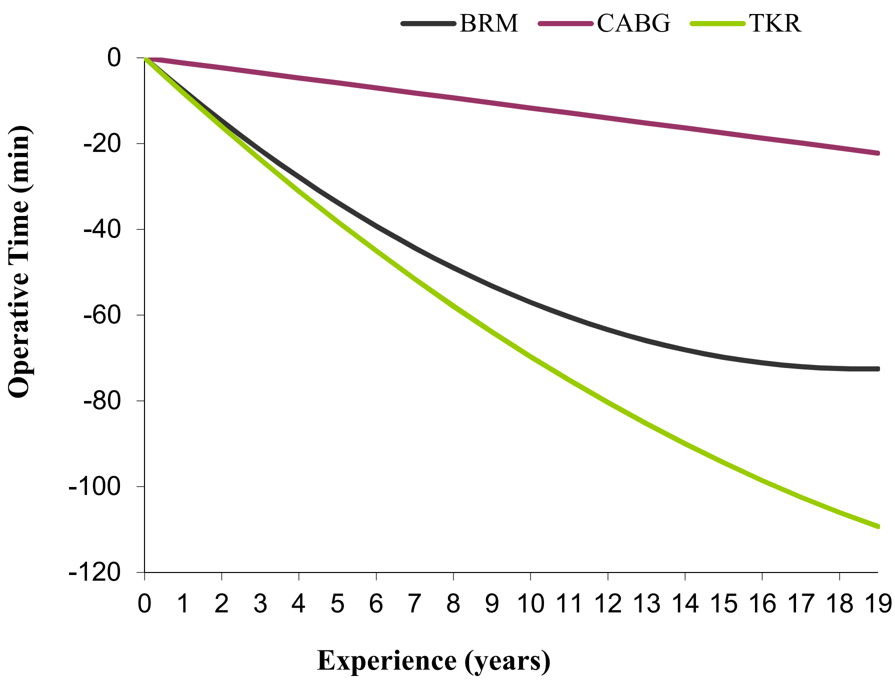
Figure 1: Learning curves for BRM, CABG and TKR

Attending surgeon experience was associated with significant reductions in operative time across all procedures, however, the nature and magnitude of the relationship was procedure specific.



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ABSTRACT

Objectives: to evaluate the learning curves of three high-volume procedures, from distinct surgical specialties.

Setting: Tertiary care academic hospital.

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- This study quantitatively characterised the learning curves of three procedures from distinct surgical specialties – total knee replacement, bilateral reduction mammoplasty and isolated coronary artery bypass grafting.
- Common trends in surgical learning were found to exist. Dependent upon the procedure, experience can serve as a powerful driver of improvement or have clinically insignificant impacts on operative time.
- In contrast to the notion that efficiency is optimised within a fairly narrow temporal window following the start of clinical practice, our data suggest that operative learning curves, for some procedures, exhibit ongoing improvement in efficiency over the course of a surgeon's career, with time courses much longer than previously anticipated.

Strengths and limitations of this study

- Use of high-granularity data on over 7000 procedures, performed by 30 surgeons; robust statistical demonstration of the effect of experience on operative efficiency.
- Single centre, retrospective, and focused on operative time, which although has clear relevance to operative efficiency and financial costs, is not a clear patient-centred outcome.

INTRODUCTION

Performance measurement and the application of quality, efficiency and safety metrics in surgery has dramatically expanded over the past two decades. This has met with variable compliance and success. The operating room (OR) represents a high-risk environment, requiring the coordination of technology, competence and resources under time pressure by the operating team [1, 2]. When combined with the technical and dexterous nature of surgery, it is apparent that several factors must be considered and accounted for to make accurate, equitable and comparable measurements of performance between surgeons. One of these factors is the learning curve inherent to operative procedures [3, 4, 5, 6, 7, 8].

Until recently, studies have lacked adequate data volume and resolution to gain an appropriate understanding of procedural dynamics, or robustly identify suitable performance metrics. Work thus far has predominantly focused on surgery at the institutional or departmental level, rather than that of the individual surgeon. Furthermore, no studies to date have compared learning curves across different surgical specialties using statistically uniform methods [8].

We performed a cross-specialty, comparative study evaluating the learning curves of three high-volume and well-defined procedures: bilateral reduction mammoplasty (BRM), isolated coronary artery bypass grafting (CABG) and total knee replacement (TKR). Our intent was to define commonalities and discrepancies in the learning curves of these procedures, and thereby identify overarching themes that may inform future surgical performance improvement efforts.

METHODS

Design and Population

Data for all CABG, TKR and BRM procedures performed at Brigham and Women's Hospital (BWH), 2001-2010, 1996-2009 and 1995-2007 respectively, were culled from a combination of electronic medical records, an electronic operative time tracking application, and physician employee databases. The datasets were filtered to exclude CABGs that were accompanied by concomitant procedures (e.g., valve surgery, MAZE, etc.); erroneously coded procedures including partial knee replacements, combined procedures and bilateral TKR procedures; gynaecomastia, resections and partial/total mastectomies; and incomplete or incorrect data entries (details of exclusion process are included in the Appendix). Datasets were subsequently filtered to only include surgeons who conducted more than 10 procedures annually, focusing on the first twenty years of the learning curve.

For CABG, the primary dependent variable was operative time defined as the sum of cardiopulmonary bypass time (CPB) and cross clamp time. For TKR and BRM, operative time was defined as the time elapsed from skin incision to skin closure. The operative experience of the attending surgeon was calculated as the difference between the date of the procedure and that of the surgeon's completion of training. This study was performed under Institutional Review Board approval (protocol 2006p000586).

Statistical Analysis

Surgical Learning Curves

The characteristics of patients and surgeons were described using absolute frequencies with percentages for categorical variables. The mean values with standard deviations and median values with minimum-maximum intervals were calculated for continuous variables.

The expected learning curve of surgeons over time was generated based on a multivariate generalized estimating equations (GEE) regression model. A number of possible shapes of learning curves were tested in order to obtain the best fitting [9]. Outcomes were adjusted for clustering of patients by surgeon, as well as patient case-mix factors (for CABG: patient age, sex, preoperative cardiogenic shock, diabetes mellitus and preoperative congestive heart failure; for TKR: patient age, sex and co-morbidities including coronary artery disease, chronic obstructive pulmonary disease, diabetes mellitus, hypertension, obesity and smoking; for BRM: volume of breast reduction) [9]. Selection of covariates for generation of case-mix models was achieved using the approach described by Collett [10]. Model estimates were obtained using the GENMOD procedures in SAS^{TM} 9.2 (SAS Institute Inc., Cary, NC, USA). The expected reductions in operative time associated with attending experience were plotted. All tests were two-tailed, and *p*-values <0.05 were considered significant.

RESULTS

Surgeon and cohort characteristics for each procedure are listed in Tables 1 and 2. Figure 1 displays the learning curve of each of the procedures. The number of procedures per surgeon per year are displayed in the Appendix.

A total of 1052 BRMs were completed by 8 surgeons. Mean attending experience was 11.3 ± 4.5 years, with a median case volume of 61 (range: 11-502). Mean operative time was 134.4 ± 34.5 minutes. Multivariate regression showed breast reduction volume to be the only case-mix factor to have a significant effect on operative time. After adjusting for patient characteristics and clustering, we found a significant association between operative time and attending surgeon experience entered both as a linear (P=0.0002) and a quadratic (P=0.0427) term in the model. Five, ten and fifteen years of experience were associated with 33.74, 57.02 and 69.82 minute reductions in operative time respectively, equating to 18.51%, 31.28% and 38.30% reductions (Table 3).

A total of 3254 CABGs were completed by 9 surgeons. Mean attending experience was 9.7 ± 5.9 years, with a median case volume of 290 (range: 52-973). Mean operative time was 180.9 ± 62.3 minutes. Multivariate regression showed the following case-mix factors to have a significant effect on operative time: patient age, sex, preoperative cardiogenic shock, diabetes mellitus and preoperative congestive heart failure. After adjusting for patient characteristics and clustering, we found a significant association between operative time and attending surgeon experience entered as a logarithmic term (P=0.0374) in the model. Five, ten and fifteen years of experience were associated with 5.85, 11.69 and 17.54 minute reductions in operative time respectively, equating to 2.61%, 5.22% and 7.83% reductions (Table 3).

A total of 3325 TKRs were completed by 13 surgeons. Mean attending experience was 14.5 ± 3.8 years, with a median case volume of 99 (range: 10-1871). Mean operative time was 101.9 ± 30.3 minutes. Multivariate regression showed the following case-mix factors to have a significant effect on operative time: patient age, sex and co-morbidities including coronary artery disease, chronic obstructive pulmonary disease, diabetes mellitus, hypertension, obesity and smoking. After adjusting for patient characteristics and clustering, we found a significant association between operative time and attending surgeon experience entered both as a linear ($P<0.0001$) and a quadratic ($P=0.0002$) term in the model. Five, ten and fifteen years of experience were associated with 38.20, 69.68 and 94.41 minute reductions in operative time respectively, equating to 19.60%, 35.75% and 48.44% reductions (Table 3).

DISCUSSION

We performed a cross-specialty evaluation of learning curves in surgery, investigating over 7,000 procedures performed by 30 attending surgeons. By comparing these learning curves using statistically uniform data and techniques, our study permits identification of important commonalities and differentiations, yielding several important findings:

First, in contrast to the notion that efficiency is optimised within a fairly narrow temporal window following the start of clinical practice, our data suggest that operative learning curves, for some procedures, exhibit ongoing improvement in efficiency over the course of a surgeon's career, with time courses much longer than previously anticipated. This emphasizes the necessity to draw equitable comparisons between surgeons at similar stages of the learning curve [11, 12], and supports proposals for continual monitoring, training and behavioural interventions aiming to accelerate operative maturation [13].

Second, our results demonstrate the different learning curve dynamics that exist between procedures. BRM is typified by an initial phase of variability, followed by a period of rapid improvement, followed by a relative plateau phase. TKR and CABG, on the other hand, demonstrate a more linear improvement over time. Such findings suggest that certain procedures may demonstrate characteristic learning curves, with some achieving maturation more rapidly than others. The factors contributing to these characteristics should be the subject of further investigation.

Third, the magnitude of improvements in efficiency over time varies from procedure to procedure. In some cases, efficiency is markedly augmented with increasing surgeon experience (BRM and TKR); in others, however, the improvement is substantially more marginal, and possibly clinically insignificant (CABG; <10% reduction after fifteen years of experience). This observation may be because cardiothoracic fellows begin their training as proficient and highly competent general surgery graduates. As demonstrated by previous studies, this may result in attendings achieving a significant portion of their maturation as CABG surgeons during their cardiothoracic fellowship [14, 15, 16], diminishing the impact of subsequent increases in experience. Superimposed on this is the possibility that plastic and orthopaedic surgeons may learn a broader range of procedures during their training than cardiothoracic surgeons, precluding as much experience to be gained in a given operative technique – a difference of breadth and depth. This observation suggests that interventions aiming to accelerate surgical experience acquisition, such as simulation training, may be particularly effective for enhancing efficiency in TKR and BRM, but possibly less so in CABG, given the differential impact of individual surgeon experience across these procedures.

In addition to this, procedural learning curves were found to have differential sensitivities to case-mix factors. BRM was only affected by breast reduction volume; in contrast, the TKR learning curve was found to be influenced by a variety of patient-factors including age, sex and co-morbidities. This differential is no doubt due, at least in part, to varying tolerances on the part of surgeons in each of the highlighted specialties to operate on patients with marginal health status; this must be taken into consideration when making cross-procedural comparisons.

Importantly, the development of experience-based learning curves, like those elucidated in this study, has the potential to inform efforts to prospectively monitor individual surgical performance metrics on an ongoing basis. Through the application of iterative quality improvement systems such as statistical process control (SPC), the depicted learning curves could be utilised as a baseline against which to chart the progress of surgical personnel – whether to meet administrative or educational goals [17, 18]. Such methodologies are designed to first identify and then address unwarranted variation in clinical processes, which generally leads to substantial improvements in efficiency, safety and quality. While initially conceived for the manufacturing industry, they have recently been recognised as having increasing relevance to the healthcare sphere [19, 20]. Compared to more traditional approaches of quality control, they offer a more accurate means of assessing performance and guiding improvement initiatives, particularly when they are, as in the case of the data presented here, tailored to a specific operative procedure [11, 12].

Implementation of SPC offers several potential benefits. Through improvement of surgical performance, these efforts have the potential to simultaneously improve surgical efficiency, safety, quality and cost at both the individual and institutional levels. In the context of training, mapping of performance throughout a surgeon's career will permit the evolution of young trainees to be monitored, giving rise to appraisals based upon performance rather than career chronology alone, potentially ensuring progression only upon acquisition of sufficient expertise [3, 11, 12, 21]. Deconstruction of the performance curve and comparison of curves between high and low performers will permit the elements contributing to training to be dissected. By doing so, the mechanics of surgical learning will be better understood, providing methods by which the learning curve can be accelerated. SPC methodology also presents a means of accurately assessing the efficacy of new training tools or simulation programs at the individual level, both rapidly and sensitively. Finally, this methodology may have the capacity to identify deteriorations occurring towards the end of a surgeon's career, serving as a safety monitor, and supplementing the introduction of continuing education programs [4, 22].

These implications, however, must be considered in the context of this study's limitations:

1) Our focus on operative efficiency as an outcome for CABG, TKR and BRM did not explicitly incorporate considerations related to surgical safety such as complication rates, which may be considered more patient focused. However, in a variety of work both within surgery and outside, time of task completion has been used as a robust indicator of learning and outcome [3, 23, 24, 25, 26, 27]. Studies have indicated that faster completion of the TKR procedure is associated with better outcomes [28]. Further, operative times in CABG are closely linked with patient outcome; specifically, elevated CPB times are associated with increased risks of stroke and renal failure [29].
2) We performed a retrospective investigation at a single academic medical centre, which may be criticised for limiting data quality. This approach, however, removed any Hawthorne effect with regard to efficiency assessment. We also did not account for changes in technology, operative technique, or local hospital resources occurring during the retrospective capture of our analysis.
3) Our investigation utilised years of training and/or practice as a proxy for surgical experience, rather than number of cases performed. The latter may have permitted volume-efficiency relationships to be better elucidated, and for the specific number of cases re-

quired to reach maturation to be determined. This limitation is due to our inability to capture procedures performed at other institutions by surgeons in our study cohort, either before or during the study phase; for the TKR and BRM datasets, several of the surgeons included in the dataset performed procedures elsewhere; for the CABG dataset, most of the surgeons operated exclusively at the host institution (with the exception of one). However, years of training and/or practice has been utilised as an acceptable substitute for surgical experience in prior published studies in the surgical literature [3, 4, 8, 11, 12, 30].

4) Additional controls could have been incorporated into the model, such as team familiarity, team experience, fellowship-status and the presence of a resident. Although cross-specialty analyses of such work have yet to be conducted, evidence exists at the procedure-specific level [16, 30].

This study quantitatively characterised the learning curves of three procedures from distinct surgical specialties. We identified common trends in surgical learning and demonstrated that, dependent upon the procedure, surgical experience can serve as a powerful driver of improvement or have clinically insignificant impacts on efficiency. Appreciation of these findings may guide implementation of performance-tracking and quality-improvement strategies in surgery.

Surgical Learning Curves

Table 1: Overview of study participants

		BRM	CABG	TKR
Surgeon	Attending surgeons (n)	8	9	13
	Mean experience, years (SD)	11.3 (4.5)	9.7 (5.9)	14.5 (3.8)
	Min-Max experience (years)	1-19	1-19	1-19
	Median volume of cases	61	290	99
	Range of cases	11-502	52-973	10-1871
Patients	Total number of cases	1052	3254	3325
	Mean patient age, years (SD)	36.4 (12.4)	65.8 (10.4)	66.0 (11.2)
	Female sex (%)	100	23.7	69.0
	Mean size of breast reduction reduction (SD)	1681.3 (934.4)	-	-
	Coronary artery disease (%)	2.3	100.0	21.4
	Chronic obstructive pulmonary disease (%)	12.9	9.9	6.4
	Diabetes mellitus (%)	5.6	38.0	17.9
	Obesity (%)	33.1	34.9	25.9
	Smoking history (%)	6.6	41.6	15.9
	Cardiac Heart Failure (%)	-	24.2	-
	Preoperative Cardiogenic Shock (%)	-	2.3	-

Table 2: Surgeon and statistical model characteristics

Surgical Procedure	**BRM**	**CABG**	**TKR**
Factors included in patient case-mix adjustment	Breast Reduction Volume	Age, Sex, Preoperative Congestive heart failure, Preoperative cardiogenic shock, Diabetes mellitus	Age, Sex, Coronary artery disease, Chronic obstructive pulmonary disease, Diabetes mellitus, Hypertension, Obesity Smoking
Time period data available	13 years (1/18/1995-12/21/2007)	9 years (05/01/2002-09/30/2010)	14 years (07/28/1999-06/29/2009)
No. surgeons	8	9	13
No. surgeon-years	52	48	123
No. procedures	1052	3254	3325
Median No. procedures per surgeon (min-max)	61 (11-502)	290 (52-973)	99 (10-1871)
Mean operative time (SD)	134.4 (34.5)	180.9 (62.3)	101.9 (30.3)
Model	GEE (clustering and case-mix adjusted; linear and quadratic model used)	GEE (clustering and case-mix adjusted; logarithmic model used)	GEE (clustering and case-mix adjusted; linear and quadratic model used)

Table 3: Learning curve – reductions in operative time with surgical experience

	BRM			CABG			TKR		
Experience	Operative time reduction (mins)	Total operative time (mins)	Operative time reduction (%)	Operative time reduction (mins)	Total operative time (mins)	Operative time reduction (%)	Operative time reduction (mins)	Total operative time (mins)	operative time reduction (%)
0	0	193.3097	0.0%	0	223.24841	0.0%	0	200.1773	0.0%
1	-7.5867	185.723	3.9%	-1.1694099	222.079	0.5%	-8.1803	191.997	4.1%
2	-14.7546	178.5551	7.6%	-2.3388198	220.90959	1.0%	-16.0912	184.0861	8.0%
3	-21.5037	171.806	11.1%	-3.5082297	219.74018	1.6%	-23.7327	176.4446	11.9%
4	-27.834	165.4757	14.4%	-4.6776396	218.57077	2.1%	-31.1048	169.0725	15.5%
5	-33.7455	159.5642	17.5%	-5.8470495	217.40136	2.6%	-38.2075	161.9698	19.1%
6	-39.2382	154.0715	20.3%	-7.0164594	216.23195	3.1%	-45.0408	155.1365	22.5%
7	-44.3121	148.9976	22.9%	-8.1858693	215.06254	3.7%	-51.6047	148.5726	25.8%
8	-48.9672	144.3425	25.3%	-9.3552792	213.89313	4.2%	-57.8992	142.2781	28.9%
9	-53.2035	140.1062	27.5%	-10.524689	212.72372	4.7%	-63.9243	136.253	31.9%
10	-57.021	136.2887	29.5%	-11.694099	211.55431	5.2%	-69.68	130.4973	34.8%
11	-60.4197	132.89	31.3%	-12.863509	210.3849	5.8%	-75.1663	125.011	37.5%
12	-63.3996	129.9101	32.8%	-14.032919	209.21549	6.3%	-80.3832	119.7941	40.2%
13	-65.9607	127.349	34.1%	-15.202329	208.04608	6.8%	-85.3307	114.8466	42.6%
14	-68.103	125.2067	35.2%	-16.371739	206.87667	7.3%	-90.0088	110.1685	45.0%
15	-69.8265	123.4832	36.1%	-17.541148	205.70726	7.9%	-94.4175	105.7598	47.2%
16	-71.1312	122.1785	36.8%	-18.710558	204.53785	8.4%	-98.5568	101.6205	49.2%
17	-72.0171	121.2926	37.3%	-19.879968	203.36844	8.9%	-102.427	97.7506	51.2%
18	-72.4842	120.8255	37.5%	-21.049378	202.19903	9.4%	-106.027	94.1501	53.0%
19	-72.5325	120.7772	37.5%	-22.218788	201.02962	10.0%	-109.358	90.819	54.6%

CONTRIBUTORSHIP STATEMENT

Author's contributions: study concept and design (AD, DPO, MJC, MM, SL); data collection (MJC, MM) and analysis (AD, SL); manuscript preparation (AD, MJC, MM) and revision (AD, DPO, MJC, MM, SL).

COMPETING INTERESTS

None.

Financial Disclosure and Products Statement

None of the participating authors has a conflicting financial interest related to the work detailed in this manuscript, nor do any of the authors maintain a financial stake in any product, device or drug cited in this report. Ethical and institutional board approval was granted prior to conducting this study. Information on data used in this report is available upon request.

DATA SHARING

No additional data available.

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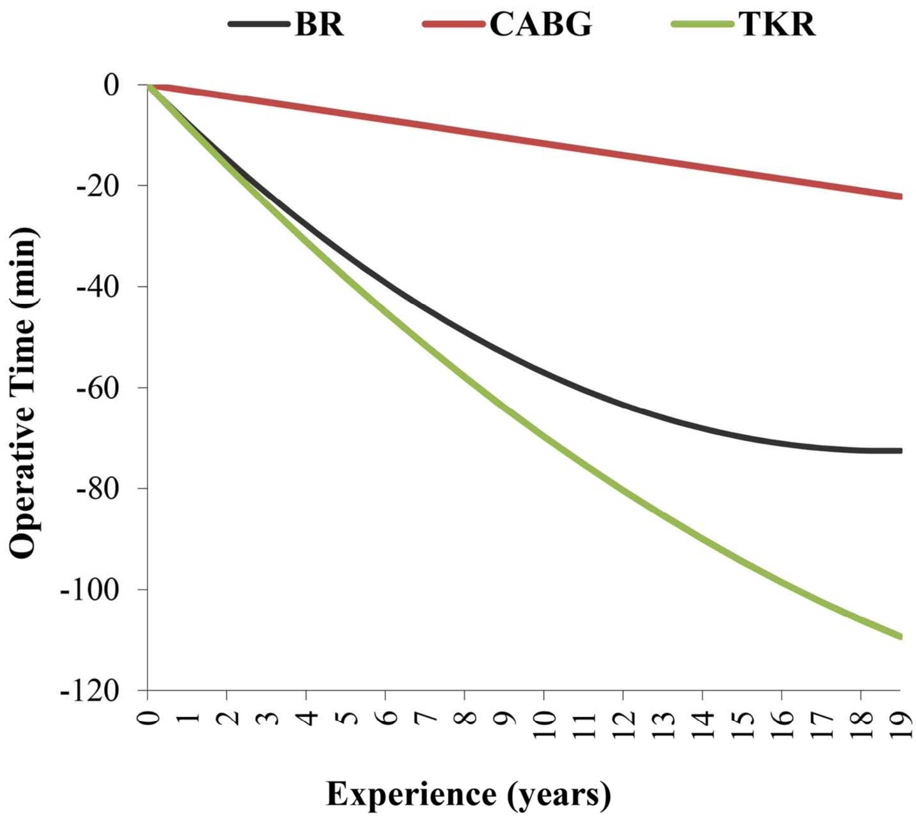

144x120mm (300 x 300 DPI)

APPENDIX

Cases included in the study, after application of exclusion criteria:

Bilateral Reduction Mammoplasty
Initial dataset = 1068
Exclusion criteria: Missing values related to year of procedure, operative time, surgeon ID, surgeon experience or size of reduction = 0
Exclusion criteria: Procedures performed by surgeon experience >19 years = 16
Exclusion criteria: Procedures performed by surgeon with overall volume<10 procedures = 0
Final dataset = 1052

CABG
Initial dataset = 4068
Exclusion criteria: Missing values related to year of procedure, operative time, surgeon ID, surgeon experience, patient demographics or comorbidities = 286
Exclusion criteria: Procedures performed by surgeon experience >19 years = 528
Exclusion criteria: Procedures performed by surgeon with overall volume<10 procedures = 0
Final dataset = 3254

Total knee replacement
Initial dataset = 5337 cases
Exclusion criteria: Missing values related to year of procedure, operative time, surgeon ID, surgeon experience, patient demographics or comorbidities = 0 cases
Exclusion criteria: Procedures performed by surgeon experience >19 years = 1988
Exclusion criteria: Procedures performed by surgeon with overall volume<10 procedures = 24 cases
Final dataset = 3325 cases

Number of cases per surgeon-year:

Bilateral Reduction Mammoplasty																				
Surgeon	Number of cases for each year of experience																			
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**Total**
A	8	5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14
B	0	1	2	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11
C	0	0	0	10	18	22	12	17	18	10	0	0	0	9	0	0	0	0	0	116
D	0	0	3	15	8	13	10	26	30	40	88	96	52	32	65	24	0	0	0	502
E	0	0	0	0	0	0	0	0	0	0	0	0	24	57	48	29	44	38	27	267
F	0	0	0	0	0	0	0	0	0	0	0	0	2	13	2	5	0	6	4	32
G	5	11	8	6	13	8	18	16	5	0	0	0	0	0	0	0	0	0	0	90
H	13	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20
Total cases	26	24	14	39	39	43	40	59	53	50	88	96	78	111	115	58	44	44	31	1052
No surgeons	**3**	**4**	**4**	**4**	**3**	**3**	**3**	**3**	**3**	**2**	**1**	**1**	**3**	**4**	**3**	**3**	**1**	**2**	**2**	**8**

CABG																	
Surgeon	Number of cases for each year of experience																
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**Total**
A	13	28	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52
B	33	40	41	38	29	0	0	0	0	0	0	0	0	0	0	0	0	181
C	0	46	104	87	65	67	66	0	0	0	0	0	0	0	0	0	0	435
D	0	0	0	0	0	0	0	0	2	87	20	29	12	14	11	5	0	180
E	0	60	91	123	93	119	124	85	0	0	0	0	0	0	0	0	0	695
F	0	0	0	0	4	155	130	33	0	0	0	0	0	0	0	0	0	322
G	0	0	0	0	0	0	0	0	0	0	0	0	0	104	71	66	49	290
H	24	74	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	126
I	0	0	0	0	0	0	0	0	0	1	123	132	129	196	151	133	108	973
Total cases	70	248	275	248	191	341	320	118	2	88	143	161	141	314	233	204	157	3254
No surgeons	**3**	**5**	**5**	**3**	**4**	**3**	**3**	**2**	**1**	**2**	**2**	**2**	**2**	**3**	**3**	**3**	**2**	**9**

TKR																				
	Number of cases for each year of experience																			
Surgeon	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**Total**
A	0	10	16	20	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	61
B	0	0	8	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11
C	0	0	0	0	0	0	0	0	0	0	0	5	32	28	33	25	23	10	38	194
D	0	0	0	0	0	0	0	0	0	0	2	2	6	5	4	7	8	6	7	47
E	0	0	0	0	0	0	0	5	20	22	30	13	12	18	21	10	22	27	30	230
F	0	0	0	0	0	2	11	43	19	24	30	17	29	34	3	0	0	0	0	212
G	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	14	18	17	25	83
H	0	0	0	0	4	6	8	2	5	12	7	16	19	22	34	33	18	0	0	186
I	0	0	0	0	0	0	0	0	4	6	6	8	12	31	34	37	41	37	46	262
J	0	0	0	0	0	0	0	0	0	0	3	2	5	6	12	13	15	16	27	99
K	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
L	0	0	0	0	0	0	0	9	13	23	11	3	0	0	0	0	0	0	0	59
M	0	0	0	0	0	0	43	66	52	77	72	88	103	168	194	244	240	242	282	1871
Total cases	10	10	24	23	19	8	62	125	113	164	161	154	218	312	344	383	385	355	455	3325
No surgeons	**1**	**1**	**2**	**2**	**2**	**2**	**3**	**4**	**6**	**5**	**8**	**9**	**8**	**8**	**9**	**8**	**8**	**7**	**7**	**13**