Learning Minimally-Invasive Mitral Valve Surgery: A Cumulative Sum Sequential Probability Analysis of 3895 Operations from a Single High Volume Center

Running title: Holzhey et al.; Learning minimally-invasive mitral valve surgery

David M. Holzhey, MD, PhD; Joerg Seeburger, MD; Martin Misfeld, MD, PhD; Michael A. Borger, MD, PhD; Friedrich W. Mohr, MD, PhD

Department of Cardiac Surgery, Heart Center Leipzig, Leipzig, Germany

Address for Correspondence:
David M. Holzhey, MD, PhD
Heart Center Leipzig
Struempellstrasse 39
04289 Leipzig, Germany
Tel: 49 341 878 1788
Fax: 49 3212 1060 377
E-mail: dholzhey@web.de

Journal Subject Code: Cardiovascular (CV) surgery:[38] CV surgery: valvular disease
Abstract:

Background—Learning curves are vigorously discussed and viewed as a negative aspect of adopting new procedures. However, very few publications have methodically examined learning curves in cardiac surgery, which could lead to a better understanding and a more meaningful discussion of their consequences. The purpose of this study was to assess the learning process involved in the performance of minimally invasive surgery of the mitral valve (MIS-MV) using data from a large, single center experience.

Methods and Results—All mitral (+/-tricuspid, +/-atrial fibrillation ablation) operations performed over a 17-year period through a right lateral mini-thoracotomy with peripheral cannulation for cardiopulmonary bypass (n = 3907) were analysed. Data were obtained from a prospective database. Individual learning curves for operation time and complication rates (using sequential probability cumulative sum failure analysis) and average results were calculated. A total of 3895 operations by 17 surgeons performing their first MIS-MV operation at our institution could be evaluated. The typical number of operations to overcome the learning curve was between 75 and 125 operations. Furthermore, more than one such operation per week was necessary to maintain good results. Individual learning curves varied markedly proving the need for good monitoring and/or mentoring in the initial phase.

Conclusions—A true learning curve exists for MIS-MV operations. Although the number of operations required to overcome the MIS-MV learning curve is substantial, marked variation exists between individual surgeons. Such information could be very helpful in structuring future training and maintenance of competence programs for this kind of surgery.

Key words: mitral valve, surgery, learning curve
Introduction

Minimally invasive surgery of the mitral valve (MIS-MV) has become the routine approach to mitral valve disease in some centers, particularly in Europe, with excellent short and long term results. However, most reports come from high volume centers with a large experience in these techniques. Surgeons at other centers might be reluctant to adopt the minimally invasive approach because of the initial learning curve that is involved. Although several publications have discussed the learning curve associated with MIS-MV operations, such publications are expert opinion only with little supportive data.

For many operators it remains a question if the potential benefits of MIS-MV -- such as reduced respiratory support, less pain, improved cosmetics, and lower risk of wound infections -- can outweigh the potential drawbacks of an initially higher complication rate when adopting a new approach. In fact, some experts have argued that the learning curve for minimally invasive procedures should prevent its widespread implementation. To the best of our knowledge, however, no study to date has methodically examined the true learning curve for MIS-MV.

The purpose of our study was to therefore analyse and compare the learning curves of surgeons who have started performing MIS-MV operations at our institution, to calculate average trends, and to provide recommendations on the necessary experience to achieve and retain high quality outcomes in this field.

Patients and Methods

Patients

A total of 5287 patients who underwent mitral valve and/or tricuspid valve surgery and/or atrial fibrillation ablation therapy between 1994 and 2011 at our institution were analysed. Patients
undergoing other concomitant procedures -- such as coronary bypass surgery, aortic valve replacement, or aortic surgery -- were excluded. Nine patients undergoing robotic mitral valve surgery by both staff and guest surgeons were also excluded. Such procedures were never performed on a routine basis at our center because of time and resource utilization. Of the 5287 patients, 3907 (74%) were operated on using a MIS-MV technique. The percentage of MIS-MV varied over time and is shown in Table 1. The 3907 operations were performed by a total of 21 surgeons who gained their first clinical experience with this method at our center. Four surgeons, each of whom performed fewer than 5 MIS MV operations, were excluded from further analysis because the number of outcomes of interest for these surgeons was too small for to draw meaningful conclusions. The final number of MIS-MV operations available for analysis was therefore 3895. Each of the 17 remaining surgeons had at least 2 years of independent clinical operating experience with at least 40 previous MV operations performed via a sternotomy. A learning curve analysis was made possible by the fact that the cardiac surgery unit was under the same leadership throughout the entire study period and that methods of patient selection, operative technique, and postoperative care had not markedly changed over time.

Data was drawn from a prospectively gathered database for MIS-MV housed at our institution. The study was approved for anonymous analysis by the institutional review board, with additional patient consent waived.

**Patient selection and surgical technique**

It is the policy at our institution to use the MIS-MV approach whenever possible. The main reasons for not operating minimally invasively were previous right thoracotomy with expected lung adhesions, difficulties with femoral vessel cannulation, and, in the case or urgent or emergent surgery, the non-availability of a surgeon who was versed in the MIS-MV approach.
Other possible reasons for preferring the sternotomy approach were a very low ejection fraction (in order to achieve the shortest possible crossclamp time) and expected difficulties with valve replacement because of extremely severe annular calcification or deep annular abscess. Such decisions were made at the surgeon’s discretion.

In all patients who underwent MIS-MV, a right-lateral mini-thoracotomy and femoral cannulation for cardiopulmonary bypass (CPB) with mild-to-moderate hypothermia were performed. In the vast majority of patients, a transthoracic aortic clamp as introduced by Chitwood was used. Details on the MIS-MV operative approach are described more thoroughly elsewhere. Patients who underwent robotic MV surgery were excluded.

Data analysis

Categorical variables are expressed as proportions and continuous variables as mean +/- standard deviations throughout this study. Patients were divided into groups of 50 consecutive operations each to evaluate the influence of growing surgical experience on adverse outcomes. Testing for differences between these groups was done using the chi-square test.

The primary outcome was a composite endpoint consisting of all important adverse events including intraoperative conversion to sternotomy, re-exploration for bleeding, valve related reoperation within the same hospital stay, new renal failure requiring dialysis, stroke, perioperative myocardial infarction, low cardiac output syndrome with necessity for IABP or ECMO support, or death. Patients in whom more than one of the above complications occurred were considered to have experienced only one primary outcome. The primary outcome had to occur within 30 days after the index procedure or until the first discharge from hospital, whichever was longer.

The learning process was first assessed by compiling the average complication rates (i.e.
the occurrence of the primary outcome) over all surgeons in blocks of 50 operations.

Furthermore, an analysis of the influence of the operation frequency (i.e. number of operations per week) on the principal outcome occurrence was performed.

Learning curves were then determined for each individual surgeon with regards to total operation time, aortic crossclamp time, and primary outcome rates. The learning curves for complication rates were calculated for both the experience of the whole institution and the individual performance of each surgeon.

In order to generate learning curves, we used the sequential probability cumulative sum (CUSUM) failure analysis which has been described in detail elsewhere10. In brief, the actual minus expected failure rate is plotted against the number of operations. The resulting chart runs parallel to the x-axis when the complication rate is as expected, turns upward when more complications than expected occur, and turns downward when a favourably low complication rate is observed. Additionally, boundary lines are calculated marking the borders for statistical significance.

**Results**

As stated above, surgeons with less than 20 minimal invasive MV operations were excluded. Thus 3895 operations performed by 17 surgeons could be analysed in detail. The mean number of operations per surgeon was 189 with a range from 21 to 1385. Table 2 provides a summary of important patient characteristics and postoperative complications for the entire group. Table 3 summarizes important intraoperative parameters and outcome variables.

**Average learning curves**

The learning curves with regards to selected adverse events according to the total number of
operations performed per surgeon are depicted in Figure 1. Despite the wide variation, a clear tendency towards better results with growing experience was observed. While an adverse event (i.e. conversion to sternotomy, re-exploration for bleeding, valve-related reoperation during hospitalization, new dialysis, stroke, myocardial infarction, low cardiac output syndrome, or death) was observed in almost every fourth patient at the beginning of the surgeon’s experience, this rate fell to a “normal” range of approximately 10% after 250 operations (p = 0.124). A large proportion of this observed trend was due to the falling rate of re-explorations for bleeding, reduced from 8.2% to 1.9% after 300 operations (p = 0.085). In addition, the conversion rates to sternotomy and the necessity for cardiac reoperations showed the same tendency towards improvement with increasing surgeon’s experience.

Institutional learning curve

Figure 2 depicts the learning curve of the entire institution. After a slight accumulation of failures in the early years, the learning curve became consistently downward (i.e. less complications than expected) after the 4th year of implementation of the MIS-MV program. From 2008 on, however, the complication rate started to rise again. This time point is congruent with a number of new surgeons joining the MIS-MV program. The early phases of their learning curves added up to a higher overall complication rate for the entire institution (see Figure 3). Only in 2011 did the curve start to improve again. It is important to note that a rise in the learning curve did not translate into a worse operative mortality. That is, the 30-day mortality rate remained stable throughout the last seven years of the study, consistently remaining between 1% and 2%.

For a closer analysis of which event had the highest impact on the rising institutional leaning curve, we calculated exclusion learning curves by sequentially eliminating each single complication from the analysis and comparing the resulting calculated curves. This analysis
revealed that re-exploration for bleeding played a dominant role. If it was excluded from the failure analysis, the learning curve continued to decline as expected after so many years of institutional experience (see Figure 4).

**Individual surgeon learning curves - complications**

Of the 17 surgeons who were available for analysis, 8 operators showed a “classical” learning curve with a turning point towards a lower complication rate typically following 75 to 125 operations (see Figure 5A). Five surgeons could be marked as “outperformers” (Figure 5B) with a very low rate of adverse events from the beginning of their experience, whereas 4 surgeons were identified to have too many complications breaking the line of statistical significance (“underperformers”, see Figure 5C).

**Individual learning curves - operative times**

We also analyses operative times for potential learning curves. We failed to identify typical learning curve patterns with regards to aortic crossclamp or total operative times (Figure 6). The operative times were quite stable from the beginning of each surgeon’s experience, with only little improvement over time. (Figure 6)

**Influence of operation frequency**

We also examined the influence of MIS-MV frequency (i.e. number of operations per week per surgeon) on the adverse event rate probability. As can be seen in Figure 7, a clear tendency for better results was observed if the surgeon performed MIS-MV at least twice per week. A higher frequency than 2 operations per week brought only minor further improvement in outcomes. A more detailed analysis including the absolute experience of a surgeon revealed that the above-described relation is particularly evident after the initial learning phase of 50 operations (see Figure 8).
Discussion

No prospective randomized studies comparing MIS-MV surgery to a conventional sternotomy approach exist to date. Given the strong attitudes of surgeons on both sides of the issue and the relative infrequency of mitral valve surgery, it is unlikely that such a randomized trial will ever be performed. Propensity matched comparisons of the two techniques observed similarly excellent outcomes for both types of operations, with no apparent drawbacks of the MIS-MV approach\textsuperscript{11, 12}. In addition, our study reveals an overall MV repair rate (82.4%), a rate of intraoperative repair failure (1.4%), as well as a rate of early valve related re-operation (3.1%) that is comparable to those described for sternotomy MV surgery in the literature. The percentage of patients who required MV reoperation during follow up has been described in detail in previous publications from our institution, with reoperation rates that are within the range of results published for full sternotomy MV surgery\textsuperscript{2, 3, 13}. However, these studies come from high-volume centers with vast experience in MIS-MV surgery.

The MIS-MV approach has gained increasing acceptance during the last decade, now being performed in 34% of patients undergoing isolated mitral valve surgery in Germany\textsuperscript{14}. Increased acceptance of MIS-MV is probably due to a combination of the following factors: improved instruments for surgical access with good visualization of the mitral valve, preservation of the integrity of the osseous thoracic wall, faster patient recovery, very good short and long term results with high rates of mitral valve repair, and increasing patient demand\textsuperscript{15}. Patient demand is likely to increase as knowledge of percutaneous mitral valve repair methods becomes increasingly widespread, which may lead to more surgeons adopting the MIS-MV technique.

Several concerns have been raised arguing against the widespread adoption of MIS-MV
surgery, however. An increased stroke rate possibly due to retrograde systemic perfusion has been observed in a large registry and has been discussed in detail. Pertaining to another concern that has been discussed in detail, we recorded 10 (0.26%) aortic dissections that we attributed to peripheral cannulation, cardioplegia needle insertion, crossclamping of the ascending aorta, or injury from an endoaortic balloon clamp. These complications were not related to the stage of training of the surgeon.

Other potential drawbacks include prolonged cardiopulmonary bypass and ischemic times, the associated learning curve, exposure difficulties in patients with challenging anatomy, suboptimal deairing techniques, and complex methods of cardioplegia administration.

The purpose of our study was to formally assess one of the potential drawbacks of MIS-MV surgery, i.e. the learning curve. The consistency in patient selection, surgical techniques, and perioperative management over the study period allowed us a unique opportunity to assess the MIS-MV learning curve in our institution. In addition, the large number of operations performed by a relatively large number of surgeons allowed us to compare learning curves between surgeons, and to assess the importance of operation frequency on adverse outcomes.

CUSUM analysis has been previously used to examine learning curve associated with off-pump coronary bypass surgery and minimally invasive direct coronary artery bypass, but has not been applied in the area of MIS-MV surgery. The CUSUM technique allows for monitoring of changes in perioperative mortality and morbidity during the patient care process. It can be repeated as often as desired, even after each operation, providing an almost real-time monitoring of surgical performance. We observed a large degree of variability in CUSUM failure curves according to individual surgeons. Such information may be critically important to those centers who are planning to adopt a MIS-MV program, and may be helpful in structuring
training and maintenance of competence programs.

In the current study, the calculation of average learning curves for the entire group of surgeons supplied a general impression of the learning process of this operative technique. The large standard deviation of some values indicates that average numbers should only serve as a general impression that may lead to a more thorough analysis of individual adverse outcome failure curves.

Interestingly, we did not observe an obvious learning curve with regard to operative times. This may be due to the fact that surgeons were assigned less complex patients during their initial MIS-MV experience. Operative times do not usually play a decisive role in patient outcomes, however, as long as they are not excessively long.

The results of our analysis for adverse outcomes support the hypothesis that MIS-MV surgery has a prolonged learning curve, even in a center performing a large volume of MIS-MV operations. The learning curve is particularly noteworthy given that all surgeons in the current study already had significant prior experience with mitral valve surgery performed through a sternotomy (at least 40 operations). Although substantial inter-surgeon variability existed, a higher complication rate during the beginning phase of MIS-MV adoption was the rule, rather than the exception. In addition, we found that the performance of more than one MIS-MV operations per week was associated with the best outcomes.

It should be stressed, however, that the predominant driving factor behind our observed learning curve was the requirement for rethoracotomy for bleeding. Removal of this complication from our composite adverse event outcome resulted in a much more favourable view of the learning curve for the entire group of surgeons (Figure 4). Our observed rethoracotomy for bleeding rate (7.2%) appears higher than observed resternotomy rates for full
sternotomy mitral valve repair surgery (0.9 – 4.4%)\textsuperscript{12, 21} Reoperation for bleeding may represent a drawback of MIS-MV surgery, probably because of visualization of the entire operative field cannot be performed with direct vision. Our elevated rethoracotomy rate led us to incorporate other methods in order to minimize the chance of this complication occurring (eg. using the thoracoscope to thoroughly inspect the inner thoracic wall before closing the incision).

Throughout the years, the MIS-MV program has always been confined to a relatively small number of surgeons (i.e. approximately 3 to 5). A new surgeon was trained only if it was foreseeable that another would leave the clinic. In 2011, for instance, 367 procedures were performed by 5 surgeons (96, 86, 43, 70, and 72 procedures per surgeon), while another beginner in this field did 13 procedures. One of the major questions of the analysis was if this restriction to so few surgeons is a reasonable strategy, since the right lateral approach is not the exception but the rule for MV surgery at our center. We can conclude from the results of the current study that this strategy was correct and it will remain unchanged in the future.

Our observed number of operations to overcome the learning curve (approximately 75 to 125) and to maintain optimal results (more than 50 per year) are somewhat sobering given that the average number of MV operations performed per surgeon per year is six in the United States\textsuperscript{22} One can conclude from our observations that MIS-MV surgery should probably be restricted to high-volume centers with a relatively large and stable number of mitral valve operations, and that the number of surgeons performing these procedures should be limited within these centers.

Despite our observations, we strongly believe that MIS-MV surgery is beneficial for patients and that surgeons should not be completely discouraged from adopting these procedures. Technical “tips” can be learned from programs with established MIS-MV programs\textsuperscript{23}. Exposure
to MIS-MV techniques as a resident (particularly to patient setup, femoral cannulation, and mitral valve exposure) and further post-fellowship training after becoming familiar with mitral valve repair techniques via a full sternotomy, should lead to minimization of the learning curve. In addition, careful patient selection should be implemented during the initial phase of the program. For example, initial MIS-MV operations should be restricted to preferably male patients who are non-obese and have a simple mitral valve pathology (eg. isolated P2 prolapse). Finally, institutional factors such as volume of mitral valve operations, dedicated cardiac anesthesia, and familiarity with minimal invasive cardiopulmonary bypass methods should also be considered. With these caveats in mind, we believe establishment of a MIS-MV program is feasible and beneficial.

Once a MIS-MV institutional program is established, our experience suggests that a close monitoring system for patient outcomes using appropriate statistical methods should be performed. If an excess of complications is observed or if a statistical underperformer is identified, further action may be required. In our institution, for example, our CUSUM analysis lead to a higher awareness for the most frequent complication (i.e. re-thoracotomy for bleeding) and focused our attention on methods to minimize it from occurring).

In our opinion, a surgeon who has been trained for MIS-MV surgery is still a valuable operator even in the face of temporary "underperformance". Oftentimes minor changes in the operative strategy can lead to significant improvements in outcome. Our policy is to therefore give MIS-MV surgeons who are underperforming a chance to benefit from a relatively short period of supervision by a very experienced senior surgeon. At our institution two surgeons went on to such a retraining phase after thorough data analysis.
Limitations

The current study is retrospective in nature and is therefore subject to the inherent weaknesses of a retrospective analysis. In addition, it depicts only a single center experience which may limit its generalizability to other centers.

Conclusions

MIS-MV surgery is associated with a prolonged learning curve. Although inter-surgeon variability was observed, a relatively large number of MIS-MV operations was required in order to overcome the learning curve. Training and maintenance of competence programs may need to be adjusted to reflect these realities. In addition, our results suggest that the adoption of MIS-MV surgery be restricted to large mitral valve volume centers.

Conflict of Interest Disclosures: None.

References:


**Table 1.** Percentage of minimal invasive mitral valve (MIS-MV) procedures over time.

<table>
<thead>
<tr>
<th>Year</th>
<th>Total number of MV operations</th>
<th>Number of MIS-MV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>1995</td>
<td>116</td>
<td>11</td>
</tr>
<tr>
<td>1996</td>
<td>125</td>
<td>13</td>
</tr>
<tr>
<td>1997</td>
<td>151</td>
<td>50</td>
</tr>
<tr>
<td>1998</td>
<td>138</td>
<td>43</td>
</tr>
<tr>
<td>1999</td>
<td>158</td>
<td>76</td>
</tr>
<tr>
<td>2000</td>
<td>144</td>
<td>91</td>
</tr>
<tr>
<td>2001</td>
<td>261</td>
<td>174</td>
</tr>
<tr>
<td>2002</td>
<td>283</td>
<td>217</td>
</tr>
<tr>
<td>2003</td>
<td>302</td>
<td>234</td>
</tr>
<tr>
<td>2004</td>
<td>308</td>
<td>263</td>
</tr>
<tr>
<td>2005</td>
<td>385</td>
<td>322</td>
</tr>
<tr>
<td>2006</td>
<td>400</td>
<td>335</td>
</tr>
<tr>
<td>2007</td>
<td>469</td>
<td>395</td>
</tr>
<tr>
<td>2008</td>
<td>516</td>
<td>455</td>
</tr>
<tr>
<td>2009</td>
<td>530</td>
<td>449</td>
</tr>
<tr>
<td>2010</td>
<td>505</td>
<td>398</td>
</tr>
<tr>
<td>2011</td>
<td>476</td>
<td>380</td>
</tr>
<tr>
<td>sum</td>
<td>5287</td>
<td>3907</td>
</tr>
</tbody>
</table>
Table 2. Patient demographics for the entire group of patients undergoing minimal invasive mitral valve surgery over the 17 year study period.

<table>
<thead>
<tr>
<th>N</th>
<th>3907</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean age</td>
<td>61.1 ± 13.0</td>
</tr>
<tr>
<td>male</td>
<td>2184 55.9%</td>
</tr>
<tr>
<td>urgent cases</td>
<td>200 5.1%</td>
</tr>
<tr>
<td>active endocarditis</td>
<td>78 2.0%</td>
</tr>
<tr>
<td>prior cardiac surgery</td>
<td>305 7.8%</td>
</tr>
<tr>
<td>mean LVEF (%)</td>
<td>59.7 ± 13.4</td>
</tr>
<tr>
<td>previous stroke</td>
<td>157 4.0%</td>
</tr>
<tr>
<td>dialysis</td>
<td>26 0.7%</td>
</tr>
<tr>
<td>pulmonary hypertension (&gt;60mmHg)</td>
<td>420 10.7%</td>
</tr>
<tr>
<td>mean additive EuroSCORE</td>
<td>4.7 ± 2.7</td>
</tr>
<tr>
<td>mean logistic Euroscore (%)</td>
<td>6.1 ± 7.3</td>
</tr>
<tr>
<td>NYHA class</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>611 15.6%</td>
</tr>
<tr>
<td>II</td>
<td>1556 39.8%</td>
</tr>
<tr>
<td>III</td>
<td>1618 41.4%</td>
</tr>
<tr>
<td>IV</td>
<td>122 3.1%</td>
</tr>
</tbody>
</table>

LVEF – left ventricular ejection fraction, NYHA – New York Hart Association

Table 3. Intraoperative variables and postoperative outcomes for the entire study group.

<table>
<thead>
<tr>
<th>N</th>
<th>3907</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intraoperative</strong></td>
<td></td>
</tr>
<tr>
<td>MV repair intended</td>
<td>3218 82.4%</td>
</tr>
<tr>
<td>MV repair failed</td>
<td>55 1.4%</td>
</tr>
<tr>
<td>MV replacement (total)</td>
<td>741 19.0%</td>
</tr>
<tr>
<td>+ TV repair</td>
<td>462 11.8%</td>
</tr>
<tr>
<td>+ atrial fibrillation ablation</td>
<td>1096 28.1%</td>
</tr>
<tr>
<td>+ PFO closure</td>
<td>365 9.3%</td>
</tr>
<tr>
<td>conversion to full sternotomy</td>
<td>65 1.7%</td>
</tr>
<tr>
<td>mean length of surgery (min)</td>
<td>179.6 56.2</td>
</tr>
<tr>
<td>mean cross clamp time (min)</td>
<td>74.2 36.0</td>
</tr>
</tbody>
</table>

| **Postoperative** | |
| low cardiac output syndrome | 92 2.4% |
| IABP | 85 2.2% |
| ECMO | 30 0.8% |
| myocardial infarction | 18 0.5% |
| valve related re-operation | 120 3.1% |
| reexploration for bleeding | 283 7.2% |
| stroke | 79 2.0% |
| sepsis | 46 1.2% |
| new dialysis | 82 2.1% |
| tracheotomy | 76 1.9% |
| 30-day mortality | 90 2.3% |

Figure Legends:

Figure 1. Average development of selected adverse events according to total number of operations performed per surgeon. The patients were divided into groups of 50 consecutive operations by the same surgeon. Mean values +- standard deviation are depicted.

Figure 2. Institutional learning curve for development of adverse events (conversion to sternotomy, re-exploration for bleeding, valve-related reoperation, new dialysis, stroke, myocardial infarction, low cardiac output syndrome, and / or death) during minimal invasive mitral valve surgery. The black dots along the x-axis indicate the first operation performed by each new surgeon in the program. The average mortality per year is also depicted (grey line).

Figure 3. Individual learning curves of all surgeons listed according to the year they started performing minimal invasive mitral valve surgery.

Figure 4. Institutional learning curves for development of adverse events. The black line displays the same adverse event complication curve shown in Figure 2. The grey line shows the learning curve after excluding re-exploration for bleeding from the analysis.

Figure 5. Examples of learning curve patterns from individual surgeons. The dashed lines depict the borders of statistical significance indicating a significantly higher (upper border) or lower than expected (lower border) failure rate. A) Classic normal learning curve pattern. B) Learning curve pattern from “outperforming” surgeon. C) Learning curve pattern from “underperforming” surgeon.
**Figure 6.** Typical examples of operative times (aortic crossclamp time and total time in operating room) according to surgeon experience. No definite learning curves could be identified with regards to operative times.

**Figure 7.** Dependency of adverse event rates on operation frequency (i.e. number of minimal invasive MV operations performed per week by the corresponding surgeon.)

**Figure 8.** Dependency of adverse event rates on surgeon absolute experience and operation frequency.
Figure 1

- **All severe complications**
  - 0% - 50%
  - Number of operations: 1 - 50, 51 - 100, 101 - 150, 151 - 200, 201 - 250, 251 - 300, 301 - 350

- **Mortality**
  - 0% - 20%
  - Number of operations: 1 - 50, 51 - 100, 101 - 150, 151 - 200, 201 - 250, 251 - 300, 301 - 350

- **Conversion to sternotomy**
  - 0% - 20%
  - Number of operations: 1 - 50, 51 - 100, 101 - 150, 151 - 200, 201 - 250, 251 - 300, 301 - 350

- **Reexploration for bleeding**
  - 0% - 20%
  - Number of operations: 1 - 50, 51 - 100, 101 - 150, 151 - 200, 201 - 250, 251 - 300, 301 - 350

- **Cardiac reoperation within hospital stay**
  - 0% - 20%
  - Number of operations: 1 - 50, 51 - 100, 101 - 150, 151 - 200, 201 - 250, 251 - 300, 301 - 350

- **Stroke**
  - 0% - 20%
  - Number of operations: 1 - 50, 51 - 100, 101 - 150, 151 - 200, 201 - 250, 251 - 300, 301 - 350
Figure 2
Figure 3
Figure 4
Figure 5
Figure 6
Figure 7

operation per week (mean of the last ten operations)

probability for serious adverse event
Figure 8
Learning Minimally-Invasive Mitral Valve Surgery: A Cumulative Sum Sequential Probability
Analysis of 3895 Operations from a Single High Volume Center
David M. Holzhey, Joerg Seeburger, Martin Misfeld, Michael A. Borger and Friedrich W. Mohr

Circulation. published online June 26, 2013;
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2013 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the
World Wide Web at:
http://circ.ahajournals.org/content/early/2013/06/26/CIRCULATIONAHA.112.001402

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in
Circulation can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office.
Once the online version of the published article for which permission is being requested is located, click Request
Permissions in the middle column of the Web page under Services. Further information about this process is
available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation is online at:
http://circ.ahajournals.org//subscriptions/