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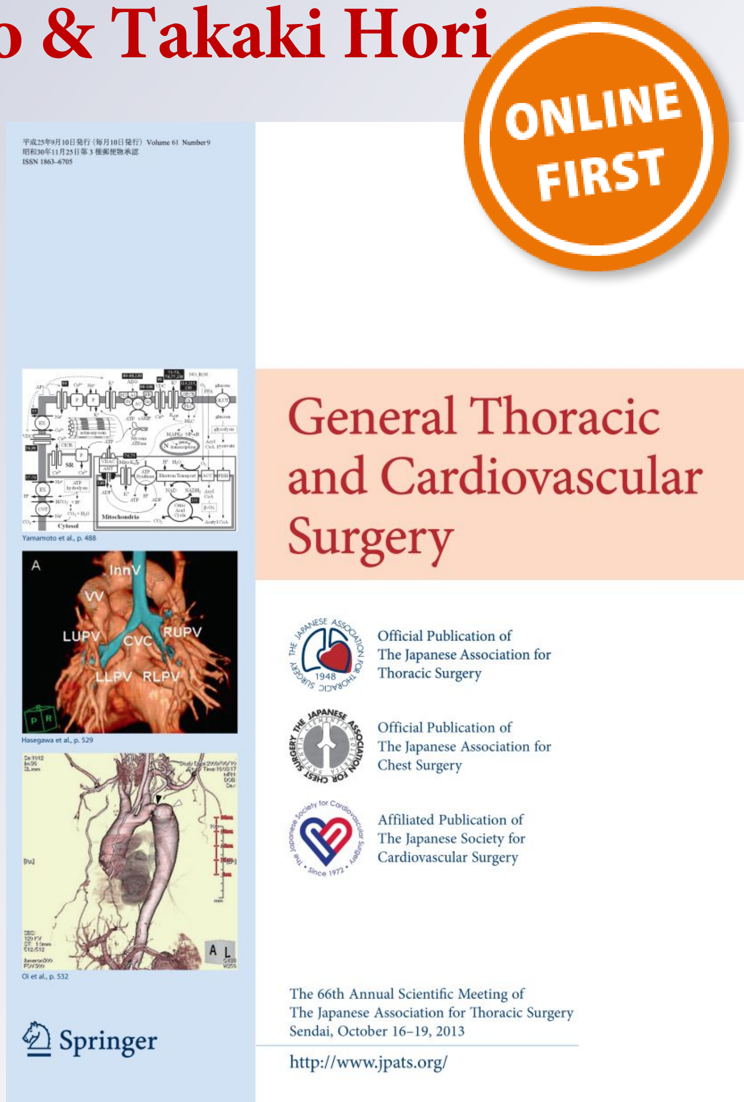

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ORIGINAL ARTICLE

The learning curve of minimally invasive aortic valve replacement for aortic valve stenosis

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Abstract

Objective Few clinical studies have been conducted to evaluate the learning curve of minimally invasive aortic valve replacement. The purpose of this study was to retrospectively analyze the learning curve of initial and isolated minimally invasive aortic valve replacement for aortic valve stenosis which performed at our institution.

Methods This study included 126 patients who underwent initial and isolated minimally invasive aortic valve replacement via right infra-axillary mini thoracotomy for aortic valve stenosis. Patients were divided into the first 50 patients [1–50 cases: E group ($n = 50$)] and the last 76 patients [51–126 cases: L group ($n = 76$)].

Results A significantly shorter operative time (239.4 ± 35.2 min vs. 206.5 ± 25.5 min, $P < 0.001$), cardiopulmonary bypass time (151.1 ± 27.4 min vs. 126.9 ± 20.2 min, $P < 0.001$) and aortic cross-clamp time (115.2 ± 19.0 min vs. 93.9 ± 14.7 min, $P < 0.001$) were found in the L group. The learning curves of operative time, cardiopulmonary bypass time, and aortic cross-clamp time plateaued after 40 cases.

Conclusions Learning curves were observed in surgical processes such as operative time. A total of 40–50 cases are required to achieve a stable operative time. However, patient outcomes were not significantly different between the groups. This study could be helpful in introducing minimally invasive aortic valve replacement and designing training programs.

Keywords Minimally invasive cardiac surgery · Aortic valve replacement · Minimally invasive aortic valve replacement · Learning curve

Introduction

The progress of minimally invasive cardiac surgery (MICS) in recent years has resulted in its rapid popularization as an alternative to conventional valve surgery. At the same time, quality control in cardiac surgery has become increasingly important. Cardiac surgeons face the need to develop new techniques while maintaining high-quality results. The learning curve is an important factor in the development of new technologies and has an influence on the outcomes. Hopper et al. [1] reported that the measures of a learning curve are classified into two categories: surgical process measures and patient outcome measures. Surgical process measures include operative factors such as operative time and blood loss. Patient outcome measures include postoperative factors such as length of ICU stay, morbidity rates, and mortality rates. Surgical process outcomes are more commonly used as indirect endpoints associated with patient outcomes since the latter are more difficult to analyze.

Since Benetti et al. [2] first reported on MICS for aortic valve replacement (AVR) with a right anterolateral mini-thoracotomy approach in 1997, some publications have shown good early outcomes compared to conventional AVR [3, 4]. However, only a few clinical studies have been conducted to evaluate the learning curve of MICS-AVR. Therefore, the purpose of this study was to retrospectively analyze the learning curve of initial and isolated MICS-AVR for aortic valve stenosis (AS) performed at our institution.

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Patients and methods

Patients

A total of 467 patients underwent MICS at our institution between May 2014 and December 2018. All procedures were performed by a single surgeon. Of the 467 patients, 188 patients underwent initial and isolated MICS-AVR via right infra-axially mini-thoracotomy. A total of 452 AVR procedures were performed in the same period. Among them, 126 patients underwent initial and isolated MICS-AVR for AS and were included in the study. Patients were divided into groups of the first 50 patients (1–50 cases: E group) and the last 76 patients (51–126 cases: L group). The study chart of the study is shown in Fig. 1.

At the beginning of the study, MICS was only performed in patients in which full sternotomy presented a high risk. However, currently, exclusion criteria for MICS are as follows: calcified ascending aorta, history of right lung surgery, poor left ventricle (LV) function (ejection fraction < 30%), poor lung function (forced expiratory volume during the first second < 1L). Data were obtained from our institutional database. This study was approved by the local institutional review board.

Surgical procedure

After general anesthesia with differential lung ventilation, patients were placed in a 20° left lateral position with a pillow under the left thorax. A skin incision was made forward from the right anterior axillary line. After dissecting the space under the pectoralis major muscle anteriorly, a thoracotomy incision was made through the third intercostal space. The right femoral artery and vein were cannulated to establish a cardiopulmonary bypass (CPB). If the femoral artery cannulation was difficult, the right axillary artery was chosen. Right femoral venous cannulation was performed under trans-esophageal echography guidance. Vacuum assistance was used for venous drainage. A LV venting tube was inserted from the right upper pulmonary vein through the 3rd intercostal space and the patient was cooled to 32 °C. After insertion of the aortic root cannula, the ascending aorta was cross clamped using a Cygnet flexible clamp (Vitalitec Inc., Plymouth, MA, USA) through the main incision. All procedures were performed under direct vision with thoracoscopy assistance and all sutures were tied down with the aid of a knot pusher. The AVR procedure was the same as that of conventional AVR.

Statistical analysis

Continuous data are presented as mean ± standard deviation and were analyzed using a *t* test for independent samples. Categorical variables are given as frequencies and percentages and were compared using the Chi-squared test. A P value < 0.05 was considered statistically significant. We assessed the trend line of the calculated logarithmic approximation of operative time, CPB time, and aortic cross clamp (ACC) time. All data were analyzed using Statcel4 software (OMS publishing Inc., Tokyo, Japan).

Results

Patient characteristics

Patient characteristics are summarized in Table 1. There were no significant differences between groups in age (73.6 ± 8.9 years vs. 75.9 ± 7.6 years, $P = 0.22$), body surface area (1.53 ± 0.15 m^2 vs. 1.49 ± 0.19 m^2, $P = 0.38$) and prevalence of male sex (46 vs. 38%, $P = 0.38$). Compared to the E group, European System for Cardiac Operative Risk Evaluation II (EuroSCORE II) was significantly lower in the L group (3.30 ± 3.02 vs. 1.82 ± 1.40, $P = 0.002$). Although a significantly lower prevalence of steroid use was observed in the L group, no significant differences were found in other risk factors between groups.

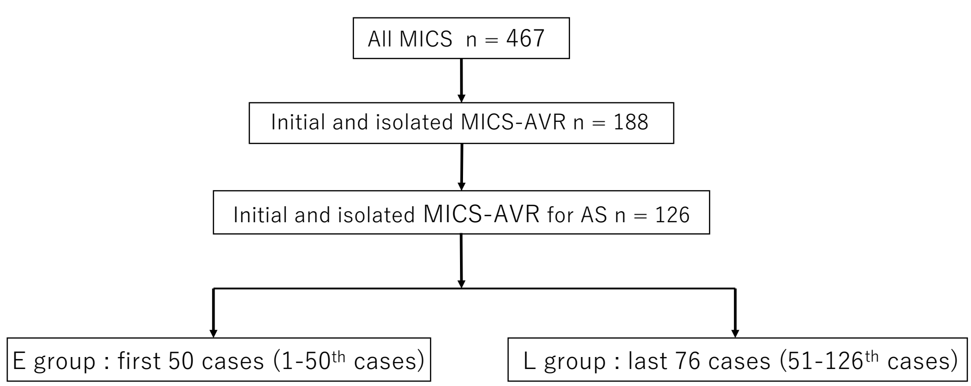

Fig. 1 Study flow chart

Operative data

Operative data are summarized in Table 2. Compared to the E group, a significantly shorter operative time (239.4 ± 35.2 min vs. 206.5 ± 25.5 min, $P < 0.001$), CPB time (151.1 ± 27.4 min vs. 126.9 ± 20.2 min, $P < 0.001$) and ACC time (115.2 ± 19.0 min vs. 93.9 ± 14.7 min, $P < 0.001$) were found in the L group. The learning curves of operative time, CPB time, and ACC time are shown in Fig. 2. All curves plateaued after 40 cases. The prevalence of bioprosthetic valve use and the size of the implanted prosthetic valve was not significantly different between groups (96 vs. 97%, $P = 0.67$, 20.2 ± 1.7 mm vs. 20.2 ± 1.7 mm, $P = 0.82$). The prevalence of closed-circuit use was significantly lower

Table 1 Patient characteristics

	All (*n* = 126)	E group (*n* = 50)	L group (*n* = 76)	*P* value
Age (years)	75.0 ± 8.2	73.6 ± 8.9	75.9 ± 7.6	0.22
Sex, male	52 (42%)	23 (46%)	29 (38%)	0.38
Body surface area (m^2)	1.51 ± 0.18	1.53 ± 0.15	1.49 ± 0.19	0.18
EuroSCORE II	2.41 ± 2.29	3.30 ± 3.02	1.83 ± 1.40	0.002
NYHA class > III	16 (13%)	7 (14%)	9 (12%)	0.72
Diabetes	28 (22%)	14 (28%)	14 (18%)	0.21
Renal failure	23 (18%)	11 (22%)	12 (16%)	0.38
Dialysis	12 (10%)	5 (10%)	7 (9%)	0.88
COPD	5 (4%)	1 (2%)	4 (5%)	0.36
Steroid use	6 (5%)	6 (12%)	0 (0%)	0.002
Ejection fraction (%)	64.0 ± 11.1	63.0 ± 11.0	64.7 ± 11.1	0.4
Cerebrovascular disease	13 (10%)	5 (10%)	8 (11%)	0.92
Peripheral artery disease	2 (1.6%)	0 (0%)	2 (2.6%)	0.25
Pulmonary hypertension	18 (14%)	9 (18%)	9 (12%)	0.33
Preoperative Hb (g/dl)	12.2 ± 1.62	12.3 ± 1.62	12.0 ± 1.62	0.26

Data are presented as *n* (%) or mean ± SD

COPD, choronic obstructive pulmonary disease; NYHA, New York Heart Association; Hb, hemoglobin

Table 2 Operative data

	All (*n* = 126)	E group (*n* = 50)	L group (*n* = 76)	*P* value
Operative time (min)	219.6 ± 33.7	239.4 ± 35.2	206.5 ± 25.5	< 0.001
CPB time (min)	136.5 ± 26.1	151.1 ± 27.4	126.9 ± 20.2	< 0.001
ACC time (min)	102.3 ± 19.5	115.2 ± 19.0	93.9 ± 14.7	< 0.001
Closed circuit use	89 (71%)	41 (82%)	48 (63%)	0.02
Bioprosthetic valve	122 (97%)	48 (96%)	74 (97%)	0.67
Valve size (mm)	20.2 ± 1.7	20.2 ± 1.7	20.2 ± 1.7	0.82
Conversion to sternotomy	1 (0.8%)	1 (2%)	0	–

CPB, cardiopulmonary bypass; ACC, aortic cross clamp

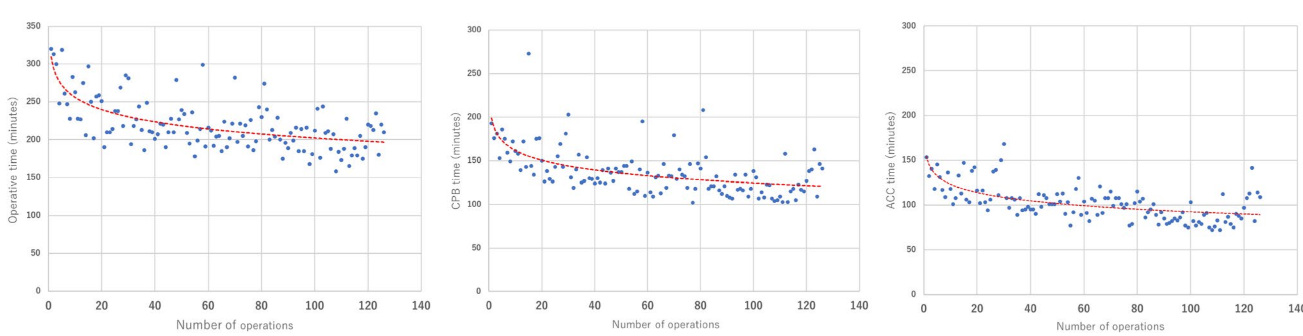

Fig. 2 Learning curves and trend lines calculated by logarithmic approximation. **a** Operative time, **b** CPB time, and **c** ACC time

in the L group (82 vs. 63%, $P=0.02$). One patient in the E group required conversion to full median sternotomy.

Postoperative data

Postoperative data are summarized in Table 3. While a significantly shorter postoperative intubation time (12.7 ± 8.4 h vs. 9.6 ± 6.5 h, $P=0.03$) was observed in the L group, the length of ICU stay (3.3 ± 1.9 days vs. 2.7 ± 1.6 days $P=0.06$) and postoperative hospital stay (13.7 ± 9.8 days vs. 11.4 ± 7.9 days, $P=0.09$) were not significantly different between groups. A significantly higher prevalence of blood transfusion [16 (32%) vs. 40 (53%), $P=0.02$] was seen in the L group.

Overall in-hospital mortality was 0.8% (1/126), which corresponds to the case in the E group that required conversion to full sternotomy. No cases of symptomatic stroke or re-exploration due to bleeding occurred and there were no significant differences in postoperative complications such as new-onset atrial fibrillation (7 vs. 13, $P=0.64$), acute renal failure (2 vs. 1, $P=0.33$), and mechanical ventilation for more than 24 h (2 vs. 4, $P=0.74$).

Discussion

This study investigated the learning curve of initial and isolated MICS-AVR both for surgical process and patient outcomes measures comparing the first 50 patients and the last 76 patients who presented our institution between May 2014 and December 2018. The results showed that a significant learning curve was observed in surgical process measures such as operative time, CPB time, and ACC time and that patient outcomes were not significantly different between groups.

In our study, operative time, CPB time, and ACC time were significantly shorter in the L group. The trend line calculated logarithmic approximation showed a relatively steep slope at the beginning and plateaued after 40 cases. Ito et al. [5] reported that ACC time, CPB time, and total operative time of the first and last 11 cases were 114 vs. 93 min, 164 vs. 129 min, and 274 vs. 221 min, respectively, and those times were significantly shorter in the later cases. Brinkman et al. [6] reported the learning curve of 90 cases of port access AVR, which were divided three groups: group 1 included cases 1 to 22, and group 2 included cases 22 to 47, and group 3 included cases 47 to 90. The mean operative times in groups 1, 2, and 3 were 302 ± 75 min, 224 ± 56 min, and 196 ± 31 min, respectively, with a significant decrease from group 1 to group 2 and a nonsignificant change between groups 2 and 3. They also reported that the learning curve plateaued after 45 to 50 cases, which was similar to findings from our study, suggesting that about 40–50 MICS-AVR procedures are needed to reach a stable operative time. Accordingly, it seems that the number of cases has a positive impact on operative time, which is one of the relevant surgical process measurements.

There was only one mortality case in the E group, and the overall mortality rate was 0.8%. There were no significant differences in major postoperative complications between groups. No cases of stroke or re-exploration were found in both groups. However, it must be considered that patient's baseline characteristics such as the EuroSCORE II were different between groups. Although the EuroSCORE II was significantly higher in the E group, no significant differences were found in other risk factors between groups except for the prevalence of steroid use, which is considered to be associated with a shift in patient selection for MICS. In early cases, MICS was performed only in patients in which full sternotomy was deemed to pose a high risk such as those with the following risk factors: steroid use, poor blood glucose control (HbA1c ≥ 8.0%), insulin use, hemodialysis, and severe obesity.

The patient who died was a 78-year-old female who presented with New York Heart Association class III heart failure symptoms and Child class B liver cirrhosis. The patient

Table 3 Postoperative data

	All ($n=126$)	E group ($n=50$)	L group ($n=76$)	P value
Operative mortality	1 (0.8%)	1 (2%)	0	–
Stroke	0	0	0	–
Re-exploration for bleeding	0	0	0	–
Prolonged ventilation (> 24 h)	6 (5%)	2 (4%)	4 (5%)	0.74
New atrial fibrillation	20 (16%)	7 (14%)	13 (17%)	0.64
Acute renal failure	3 (2.4%)	2 (4%)	1 (1.3%)	0.33
Intubation time (h)	10.8 ± 7.4	12.7 ± 8.4	9.6 ± 6.5	0.03
ICU stay (days)	2.9 ± 1.7	3.3 ± 1.9	2.7 ± 1.6	0.06
Hospital stay (days)	12.3 ± 8.7	13.7 ± 9.8	11.4 ± 7.9	0.09
Blood transfusion	56 (44%)	16 (32%)	40 (53%)	0.02
Chest tube removal (days)	2.0 ± 1.51	2.38 ± 2.07	1.79 ± 0.90	0.06

required conversion to full sternotomy and, corresponded to the 15th case of this series. Although LV ejection fraction was preserved as evaluated by transthoracic echocardiography, she presented with severe pulmonary hypertension, with an EuroSCORE II of 6.6%. After de-clamping, bleeding from the aortic root was noted and the decision was made to convert to full sternotomy. The patient died due to low output syndrome 10 days after surgery.

A significantly higher prevalence of blood transfusion was observed in the L group, which was higher than that seen in a prior study [7] and was opposite to what we expected. We use blood products when hemoglobin is lower than 8 g/dl. There was no significant difference between groups in the preoperative hemoglobin level. We prefer to use a custom-made semi-closed circuit for MICS-AVR. Our circuit is composed of an oxygenator (CAPIOX-FX, Terumo Corporation, Tokyo, Japan) and a centrifugal pump (Revolution, LivaNova, London, UK) with a cardiotomy reservoir pooling blood from suction and LV vent. The air bubble trap and elimination system are incorporated in a venous drainage line. This circuit can reduce priming volume from 900 ml to 700 ml in contrast to that in an open circuit [8]. Therefore, this could be explained by the lower use of a closed circuit in the L group. While a significantly shorter postoperative intubation time was observed in the L group, the length of ICU and hospital stay was not significantly different between groups. Our postoperative results were satisfactory from an early period and were comparable with previous studies [7, 9].

In this study, learning curves were observed in operative time, CPB time, and ACC time. In contrast, patient outcomes were not significantly different between groups. With respect to the learning curve for MICS mitral valve surgery (MICS-MVS), several studies have been conducted at high-volume centers. Holzhey et al. [10] investigated 3907 MICS-MVS procedures (82.4% were mitral valve repair intended) performed by 17 surgeons. The institutional learning curve for the development of adverse events showed a slow decrease, with the number of surgeries required to overcome the learning curve ranging from 75 to 125 cases. Murzi et al. [11] reported the learning curve using the cumulative sum (CUSUM) analysis. In a total of 936 MICS-MVS procedures (71.2% were mitral valve repairs) performed by seven surgeons, the institutional CUSUM curve showed that complications consistently declined over the first 100 cases and then became stable. Interestingly, Murzi et al. [12] also reported the learning curve of MICS-AVR using CUSUM analysis, which included the first 100 patients who underwent MICS-AVR performed by a single surgeon. The CUSUM curve showed a small initial sharp slope that was quickly replaced by a downward inflection. They concluded that patients were not exposed to an increased risk from being the initial cases. This result is similar to our conclusion. In many cases, the MVP procedure is more complex than AVR. Surgeons are confronted with a prolonged learning curve of patient outcomes in MICS-MVS. On the other hand, since the AVR procedure is identical between MICS and full sternotomy and highly reproducible, the difference in approach to aortic valve might have an influence on surgical process such as operative time but little influence on patient outcomes.

Study limitations

There are several limitations to this study. First, this study was a non-randomized retrospective observational study. The baseline characteristics of the patients, such as the EuroSCORE II were different between groups. A shift in patient selection for MICS may have had an influence on the learning curve. Additionally, transcatheter aortic valve implantation (TAVI) was introduced at our institution in November 2014 and the number of cases has been stable since late 2015. The introduction of TAVI probably had an impact on patient selection for MICS-AVR. Second, this study was performed at a single institution with a single surgeon, which may limit its generalizability to other institutions. Future studies should perform a comparison between surgeons or institutions.

Conclusions

MICS-AVR can be a safe approach with good outcomes when performed by experienced surgeons and surgical teams. In this study, a significant learning curve was observed in surgical process measures such as operative time. In contrast, patient outcomes were not significantly different between groups. Although it is presumed that 40–50 cases are required to achieve a stable operative time, our analysis revealed that MICS-AVR can be performed safely from the initial period. This study could be helpful in introducing minimally invasive aortic valve replacement and designing training programs.

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Compliance with ethical standards

Conflict of interest The authors declare they have no conflict of interest.

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