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RESEARCH

Learning curve of mini-right vertical infra-axillary thoracotomy for pediatric atrial septal defect repair: a CUSUM-based analysis

Pediatrik atriyal septal defekt onarımında mini-sağ vertikal infra-aksiller torakotominin öğrenme eğrisi: CUSUM tabanlı bir analiz

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Abstract

Purpose: Mini–right vertical infra-axillary thoracotomy (MRVIAT) is a minimally invasive technique used for pediatric atrial septal defect (ASD) repair, but its learning curve has not been clearly quantified. This study evaluated the learning curve of MRVIAT using cumulative sum (CUSUM) analysis.

Materials and Methods: This single-center retrospective study included 75 consecutive pediatric patients who underwent isolated ASD repair via MRVIAT between 2015 and 2020. CUSUM analysis of total operative time, cardiopulmonary bypass (CPB) time, and aortic cross-clamp time was performed to identify learning phases. Multivariable linear regression and segmented regression analyses were used to validate the effect of cumulative surgical experience and confirm potential breakpoints in the learning curve.

Results: Operative performance improved progressively across learning phases. Total operative time decreased significantly (126.8 ± 16.2 min vs. 103.9 ± 11.1 min vs. 91.8 ± 2.7 min). Case order remained independently associated with shorter operative time ($\beta = -0.62$ minutes per case). Segmented regression confirmed an inflection point around case 22 and performance stabilization after approximately 35–40 cases..

Conclusion: The learning curve of MRVIAT for pediatric ASD repair demonstrates rapid early improvement followed by stabilization. These thresholds should be interpreted as an individual learning curve rather than a universally generalizable benchmark.

Keywords:. Atrial septal defect, mini-right vertical infra-axillary thoracotomy, learning curve, CUSUM analysis, pediatric cardiac surgery

Öz

Amaç: Mini–sağ vertikal infra-aksiller torakotomi (MRVIAT), pediatrik atriyal septal defekt (ASD) onarımında kullanılan minimal invaziv bir cerrahi tekniktir; ancak öğrenme eğrisi nicel olarak yeterince tanımlanmamıştır. Bu çalışmada MRVIAT tekniğinin öğrenme eğrisi kümülatif toplam (CUSUM) analizi kullanılarak değerlendirildi.

Gereç ve Yöntem: Bu tek merkezli retrospektif çalışmaya 2015–2020 yılları arasında MRVIAT yaklaşımı ile izole ASD onarımı uygulanan ardışık 75 pediatrik hasta dahil edildi. Öğrenme fazlarını belirlemek amacıyla toplam operasyon süresi, kardiyopulmoner baypas (CPB) süresi ve aortik kros-klemp süresi için CUSUM analizi yapıldı. Kümülatif cerrahi deneyimin etkisini doğrulamak ve öğrenme eğrisindeki olası kırılma noktalarını belirlemek amacıyla çok değişkenli lineer regresyon ve segmentli regresyon analizleri kullanıldı.

Bulgular: Operatif performans öğrenme fazları boyunca progresif olarak iyileşti. Toplam operasyon süresi anlamlı şekilde azaldı (126.8 ± 16.2 dk, 103.9 ± 11.1 dk ve 91.8 ± 2.7 dk). Vaka sırası, operasyon süresinin kısalması ile bağımsız olarak ilişkili bulundu ($\beta = -0.62$ dakika/vaka). Segmentli regresyon analizi yaklaşık 22. vakada bir kırılma noktası ve yaklaşık 35–40. vakadan sonra performansın stabilize olduğunu gösterdi..

Sonuç: Pediatrik ASD onarımında MRVIAT tekniğinin öğrenme eğrisi erken dönemde hızlı bir iyileşme ve ardından performansın stabilizasyonu ile karakterizedir. Bu eşikler genellenebilir evrensel sınırlar olarak değil, bireysel bir öğrenme eğrisinin göstergeleri olarak değerlendirilmelidir.

Anahtar kelimeler: Atriyal septal defekt; Mini-sağ vertikal infra-aksiller torakotomi, öğrenme eğrisi, CUSUM analizi, pediatrik kalp cerrahisi

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INTRODUCTION

Atrial septal defect (ASD) is one of the most common congenital heart diseases in the pediatric population. In the presence of a hemodynamically significant left-to-right shunt, surgical or transcatheter closure may be required. Surgical ASD repair has long been established as a reliable treatment modality with low mortality and high success rates[1,2]. However, contemporary decision-making increasingly emphasizes not only surgical success but also patient-centered outcomes such as minimal invasiveness, cosmetic results, postoperative pain, recovery time, and patient–family satisfaction[3,4].

For this reason, minimally invasive surgical approaches have gained growing interest in pediatric cardiac surgery as alternatives to median sternotomy. Right thoracotomy-based techniques are preferred because of their potential to provide smaller incisions, reduced tissue trauma, and superior cosmetic outcomes. Nevertheless, the application of minimally invasive approaches in the pediatric population entails greater technical challenges compared with adult patients. Small thoracic anatomy, a limited operative field, the need for peripheral cannulation, and the fragility of intrathoracic structures render the surgical procedure more complex. Consequently, surgeon experience and team coordination play a decisive role in clinical outcomes[4-6].

Mini-right vertical infra-axillary thoracotomy (MRVIAT) is one of the minimally invasive approaches used as an alternative to sternotomy, particularly for ASD repair[4]. The incision placed along the axillary line avoids a visible anterior chest wall scar, offers high cosmetic satisfaction, and, with appropriate patient selection, can achieve early clinical outcomes comparable to conventional approaches. However, MRVIAT may present technical difficulties during surgery due to the restricted visual field and deep operative plane[7,8]. These characteristics make the learning curve a critical factor for the wider adoption of this technique.

In surgery, the learning curve refers to the predictable improvement in operative efficiency and clinical outcomes as experience with a specific technique increases. Objective definition of the learning curve is essential for patient safety, training strategies, and the establishment of new surgical programs. Demonstrating after how many cases a technique can be performed with shorter operative times and lower complication rates provides direct value for clinical practice[9]. Cumulative sum (CUSUM) analysis is a widely used method in surgical literature for evaluating learning curves, as it sensitively depicts temporal changes in performance. The CUSUM approach cumulatively tracks deviations of each case from a predefined performance benchmark, allowing objective identification of trends and potential inflection points during the learning process. Time-dependent parameters such as operative time, cardiopulmonary bypass time, and aortic cross-clamp time are particularly important indicators of technical proficiency[10].

Only a limited number of studies have addressed the learning curve of pediatric ASD repair using the MRVIAT technique. Most available reports do not comprehensively present chronological, center- and team-based performance changes[4,11]. This lack of detailed data makes it difficult, especially for centers newly adopting MRVIAT, to clearly define a safe implementation threshold and to anticipate early performance expectations.

In this study, we aimed to objectively characterize the learning curve of the MRVIAT technique for pediatric ASD repair using CUSUM analysis. The primary objective was to identify inflection points and distinct learning phases based on operative efficiency parameters, while the secondary objective was to evaluate changes in perioperative and early postoperative outcomes across these phases. We hypothesized that increasing cumulative surgical experience would be associated with progressive reductions in operative, cardiopulmonary bypass, and aortic cross-clamp times, allowing identifiable thresholds for functional proficiency and performance stabilization. The original contribution of this study is the combined use of multiparametric CUSUM analysis, multivariable regression, and segmented regression to quantitatively define and validate these learning thresholds in a consecutive single-surgeon pediatric MRVIAT series.

MATERIALS AND METHODS

Study design

This study was designed as a single-center, retrospective, observational analysis to evaluate the learning curve of the mini-right vertical infra-axillary

thoracotomy (MRVIAT) approach for pediatric atrial septal defect (ASD) repair. Consecutive cases were analyzed chronologically according to the date of surgery to objectively assess temporal changes in surgical performance.

The study was conducted at the Department of Cardiovascular Surgery, Çukurova University Faculty of Medicine, Adana, Türkiye. Surgical procedures were performed by cardiovascular surgeons, while perioperative and postoperative patient management was carried out by the responsible physicians and clinical staff according to the institutional protocols of the department. Clinical, operative, and perioperative data were retrospectively obtained from hospital medical records and operative documentation. The collected data were reviewed for completeness and consistency before statistical analysis.

The primary objective was to define the learning curve of the MRVIAT approach using cumulative sum (CUSUM) analysis. The secondary objective was to evaluate changes in perioperative and early postoperative outcomes across learning phases.

Sample

Pediatric patients who underwent primary surgical repair for isolated secundum-type atrial septal defect (ASD) at our institution between January 2015 and December 2020 were retrospectively reviewed.

Inclusion criteria were a diagnosis of isolated secundum-type ASD, primary surgical repair, availability of complete clinical and perioperative data, and procedures performed by the same surgeon. Exclusion criteria included atrioventricular septal defect (AVSD), ASD associated with other congenital cardiac anomalies (PDA, VSD, PAPVD, Ebstein anomaly, etc.), combined cardiac surgical procedures, history of reoperation, and incomplete medical records.

To ensure the homogeneity of the learning curve analysis and to allow the learning curve to reflect surgical technical performance alone, patients with additional cardiac lesions or complex congenital anomalies were excluded.

Patients were divided into two groups according to surgical approach:

- MRVIAT group: mini-right vertical infra-axillary thoracotomy
- MRALT group: mini-right anterolateral thoracotomy

The MRVIAT group constituted the primary cohort for learning curve analysis. The MRALT group served as a reference cohort for contextual evaluation of perioperative outcomes. However, because significant demographic differences existed between groups in terms of age, body weight, and body surface area, these comparisons were considered unadjusted and exploratory. Therefore, MRALT comparisons were not intended to establish superiority or equivalence but only to provide a general clinical framework.

The MRALT approach was selected as the reference because it represents an alternative minimally invasive thoracotomy technique applied during the same period. This choice allowed comparison between two approaches based on similar minimally invasive surgical principles rather than with median sternotomy, which differs substantially in invasiveness, exposure, and postoperative recovery dynamics. Consequently, sternotomy was not used as a comparison group.

Surgical approach selection was based on patient age, body surface area, thoracic anatomy, and intraoperative surgeon assessment. Accordingly, intergroup comparisons were considered exploratory and unadjusted.

Procedure

The study was conducted in accordance with the principles of the Declaration of Helsinki. Ethical approval was obtained from the Çukurova University Faculty of Medicine Research Ethics Committee (meeting no. 162; decision no. 36; date: January 9, 2026). Due to the retrospective design of the study and the use of anonymized data, the requirement for written informed consent was waived by the ethics committee.

Surgical technique

For the MRVIAT approach, patients were positioned in a right anterolateral thoracotomy position with mild elevation of the right hemithorax. A vertical skin incision approximately 4–6 cm in length was made along the right infra-axillary line. After dissection through subcutaneous tissue and muscle layers, the thoracic cavity was entered.

The pericardium was opened longitudinally and suspended with traction sutures to optimize exposure. Cardiopulmonary bypass was established using central

aortic and bicaval venous cannulation. Myocardial protection was achieved with antegrade cold blood cardioplegia.

The ASD was closed using either primary suturing or an autologous pericardial patch, depending on defect size. After repair, meticulous de-airing was performed, and cardiopulmonary bypass was weaned gradually. Following hemostasis, the pericardium was partially closed and thoracic drainage was placed.

In the MRALT approach, similar cardiopulmonary bypass and myocardial protection protocols were applied, with the thoracotomy incision performed via the anterolateral line. Identical surgical instruments, cardioplegia protocols, and postoperative care algorithms were used in both approaches.

Data collection

The following variables were recorded:

- Age, sex, body weight, body surface area
- Total operative time
- Cardiopulmonary bypass time
- Aortic cross-clamp time
- Mechanical ventilation time
- Intensive care unit (ICU) length of stay
- Hospital length of stay
- Major complications
- Conversion requirement
- Mortality

All patients were analyzed chronologically according to surgery date.

Endpoints

The primary endpoint was total operative time, selected as the principal indicator reflecting temporal changes in surgical performance and learning progression in the MRVIAT approach. Secondary endpoints included cardiopulmonary bypass time, aortic cross-clamp time, mechanical ventilation time, ICU length of stay, hospital length of stay, and early major complication rates.

Major complications were defined as residual shunt requiring reintervention, permanent pacemaker implantation, pneumothorax, significant pericardial effusion, wound infection requiring intravenous antibiotic therapy, re-exploration for bleeding, and early mortality.

Conversion was defined as unplanned intraoperative change from the MRVIAT approach to another surgical access.

CUSUM analysis

CUSUM analysis was used to evaluate the learning curve. The CUSUM value was calculated using the following formula:

$$CUSUM(n) = \Sigma (Xi - \bar{X})$$

where Xi represents the total operative time of the individual case and $\bar{X}$ represents the mean operative time of the entire MRVIAT series. The overall series mean was used as the internal reference because no validated external benchmark for MRVIAT operative time is available. This approach allows detection of relative performance changes within the series; however, the resulting thresholds are cohort-specific and should not be interpreted as externally standardized proficiency targets.

CUSUM curves were plotted sequentially by case order. A positive slope indicated operative times above the mean, whereas a horizontal or negative slope reflected performance improvement[12].

Phase definitions

Learning phases were determined based on slope changes in the CUSUM curves. Phase boundaries were not based solely on visual inspection; instead, slope inflection points were evaluated using a piecewise linear trend logic. Points where the curve transitioned from a positive slope to a horizontal or negative slope were considered indicators of significant performance change.

CUSUM curves constructed for total operative time, cardiopulmonary bypass time, and aortic cross-clamp time were evaluated together. Case numbers showing concordant slope changes across all three parameters were identified as potential phase boundaries. This multiparametric consistency approach aimed to reduce methodological bias associated with single-variable phase definitions.

Although phase boundaries were initially determined based on concordant multiparametric CUSUM slope changes, segmented regression analysis was subsequently performed to mathematically validate the identified breakpoints.

Potential phase boundaries were independently and blindly evaluated by two investigators. Only inflection points agreed upon by both investigators were accepted as final phase boundaries, ensuring that phase definition was based on both quantitative slope change and independent observational validation[13,14].

Accordingly, the learning process was divided into three phases:

- Phase I: Initial learning phase (cases 1–22)

- Phase II: Transition phase (cases 23–36)
- Phase III: Proficiency phase (cases 37–75)

Statistical analysis

Because of the retrospective design of the study, no a priori sample size calculation was performed. Instead, all consecutive patients who met the eligibility criteria during the predefined study period were included. The primary learning curve analysis comprised 75 patients who underwent MRVIAT. A sensitivity power analysis was performed to evaluate the detectable effect size for the multivariable linear regression model. Assuming a two-sided α level of 0.05, 80% statistical power, and four predictors, a sample size of 75 patients allowed detection of a minimum effect size of Cohen's $f^2 = 0.17$, corresponding to a moderate effect size.

Statistical analyses were performed using SPSS software (IBM SPSS Statistics, version 29.0, IBM Corp., Armonk, NY, USA). Distribution of continuous variables was assessed using the Kolmogorov–Smirnov and Shapiro–Wilk tests. Normally distributed data are presented as mean ± standard deviation, and non-normally distributed data as median (interquartile range, IQR). Categorical variables are expressed as number and percentage.

For comparisons between the MRVIAT and MRALT groups, normally distributed continuous variables, including age, body weight, body surface area, total operative time, cardiopulmonary bypass time, and aortic cross-clamp time, were compared using Student's t-test. Non-normally distributed continuous variables, including mechanical ventilation time, ICU length of stay, and hospital length of stay, were compared using the Mann–Whitney U test. Categorical variables, including sex, major complications, and mortality, were compared using the chi-square test or Fisher's exact test, as appropriate.

Comparisons of continuous variables among the three learning phases were performed using the Kruskal–Wallis test because the analyses involved three independent groups and the relevant variables did not meet the assumptions required for parametric testing. When the overall Kruskal–Wallis test was statistically significant, pairwise comparisons were performed using Bonferroni-corrected Mann–Whitney U tests. Categorical variables across learning phases were analyzed using the chi-square test or Fisher's exact test, as appropriate.

Mechanical ventilation time was reported as median (IQR), and the proportion of patients extubated in the operating room was analyzed as a percentage. Due to the high proportion of zero values, mechanical ventilation time demonstrated a zero-inflated distribution; therefore, non-parametric tests were used and results were interpreted based on distributional patterns.

Effect sizes for Kruskal–Wallis tests were calculated using eta-squared (η^2) and interpreted as small (0.01), moderate (0.06), and large (≥0.14). Pairwise comparisons were conducted using Bonferroni-corrected Mann–Whitney U tests.

A p value <0.05 was considered statistically significant for global tests, and $p<0.017$ for Bonferroni-corrected post-hoc comparisons.

To determine whether the observed reduction in operative time reflected a true experience-driven learning effect rather than differences in patient characteristics, multivariable linear regression analysis was performed within the MRVIAT cohort.

Total operative time (minutes) was used as the dependent variable. Case order (1–75) was included as a continuous variable representing cumulative surgical experience. Covariates were selected a priori based on their clinical relevance and their potential influence on operative time.

To minimize overfitting and multicollinearity, the following covariates were included:

- Body surface area (m^2)
- ASD closure type (primary closure = 0; patch closure = 1)
- Sex (female = 0; male = 1)

Age and body weight were excluded due to collinearity with body surface area.

To mathematically validate CUSUM-derived phase transitions, segmented (piecewise) linear regression models were constructed. Two candidate breakpoints were tested:

- Case 22 (functional proficiency threshold)
- Case 38 (stabilization threshold)

Segment variables were defined as:

post_k = max(0, case order − k)

Separate models were constructed for k=22 and k=38. Model fit was compared to evaluate whether slope changes supported the identified learning phases.

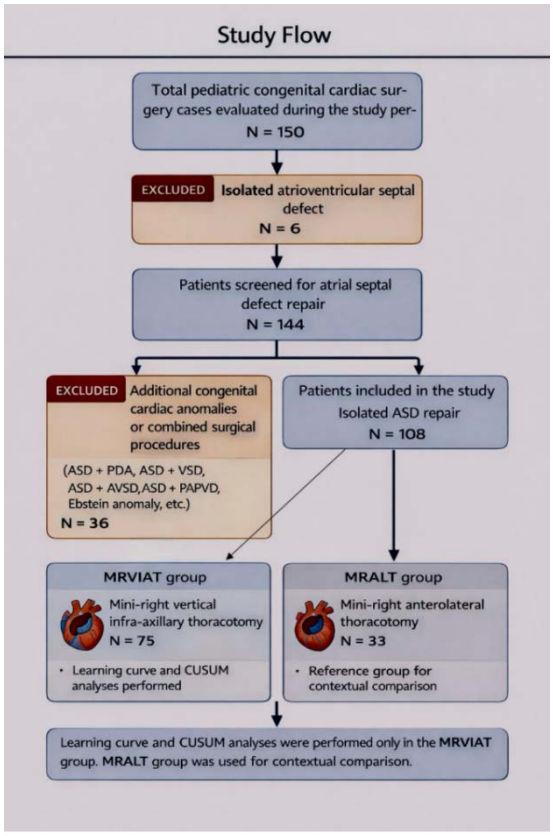


Figure 1. Study flow diagram.
Flowchart illustrating patient selection and group allocation. Between January 2015 and December 2020, pediatric patients undergoing surgical repair for atrial septal defect (ASD) were screened. Patients with non-isolated ASD, associated congenital cardiac anomalies, combined procedures, reoperations, or incomplete records were excluded. The final study population consisted of patients undergoing isolated ASD repair, who were divided according to surgical approach into the MRVIAT group (primary cohort for learning curve and CUSUM analysis) and the MRALT group (reference cohort for contextual comparison).

RESULTS

During the defined study period, a total of 150 pediatric congenital cardiac surgery cases were evaluated. Six patients operated for diagnoses other than isolated atrial septal defect (ASD) (isolated atrioventricular septal defect) were excluded. The remaining 144 patients were screened for ASD-related surgical interventions.

Among these, 36 patients with associated congenital cardiac anomalies or combined procedures (ASD + PDA, ASD + VSD, ASD + AVSD, ASD + PAPVD, Ebstein anomaly, etc.) were excluded. No patients were excluded because of previous cardiac surgery or incomplete medical records. Consequently, a total of 108 patients who underwent isolated ASD repair were included in the final analysis.

Seventy-five patients were operated using the MRVIAT approach and 33 using the MRALT approach. Learning curve and CUSUM analyses were performed exclusively in the MRVIAT group. The MRALT group was used as a reference cohort for contextual comparison of surgical and clinical outcomes [Figure 1].

The mean age was 7.92 ± 3.99 years (median: 6 years) in the MRVIAT group and 5.15 ± 1.77 years (median: 6 years) in the MRALT group. Patients in the MRVIAT group were significantly older ($p < 0.001$). Body weight was 27.88 ± 17.15 kg in the MRVIAT group and 18.48 ± 5.60 kg in the MRALT group ($p < 0.001$). Body surface area was 0.97 ± 0.38 m^2 and 0.76 ± 0.14 m^2, respectively, also showing a significant difference between groups ($p < 0.001$). Sex distribution was similar between groups (MRVIAT: 56% female, 44% male; MRALT: 51.5% female, 48.5% male; $p = 0.82$) [Table 1].

Table 1. Baseline clinical characteristics of patients with isolated ASD according to surgical approach

Variable	MRVIAT (n = 75)	MRALT (n = 33)	p value
Age (years), mean ± SD	7.92 ± 3.99	5.15 ± 1.77	<0.001
Weight (kg), mean ± SD	27.88 ± 17.15	18.48 ± 5.60	<0.001
Body surface area (m^2), mean ± SD	0.97 ± 0.38	0.76 ± 0.14	<0.001
Female sex, n (%)	42 (56.0)	17 (51.5)	0.82
Male sex, n (%)	33 (44.0)	16 (48.5)	0.82

Data are presented as mean ± standard deviation or number (percentage).
MRVIAT: mini-right vertical infra-axillary thoracotomy; MRALT: mini-right anterolateral thoracotomy; ASD: atrial septal defect; SD: standard deviation.

Operative and perioperative characteristics of the MRVIAT and MRALT groups are summarized in Table 2. Mean cardiopulmonary bypass time was 22.65 ± 8.24 minutes (median: 20; range: 10–65), and mean aortic cross-clamp time was 12.64 ± 6.12 minutes (median: 11; range: 5–40).

Table 2. Exploratory unadjusted comparison of operative and perioperative outcomes between MRVIAT and MRALT groups

Variable	MRVIAT (n=75)	MRALT (n=33)	p value
Total operative time (min), mean ± SD	104.33 ± 18.26	105.00 ± 13.17	0.850
CPB time (min), mean ± SD	22.65 ± 8.24	31.79 ± 4.04	<0.001
Cross-clamp time (min), mean ± SD	12.64 ± 6.12	16.58 ± 2.25	<0.001
Mechanical ventilation time (h), median (min–max)	0 (0–8)	0 (0–6)	0.026
ICU stay (h), median (min–max)	18 (12–48)	18 (12–28)	0.747
Hospital stay (days), median (min–max)	4 (2–9)	4 (2–6)	0.262
Major complications, n (%)	3 (4.0)	0 (0)	0.551
Mortality, n (%)	0 (0)	0 (0)	1.000

Data are presented as mean ± standard deviation or median (minimum–maximum).
MRVIAT: mini-right vertical infra-axillary thoracotomy; MRALT: mini-right anterolateral thoracotomy; CPB: cardiopulmonary bypass; ICU: intensive care unit; SD: standard deviation.

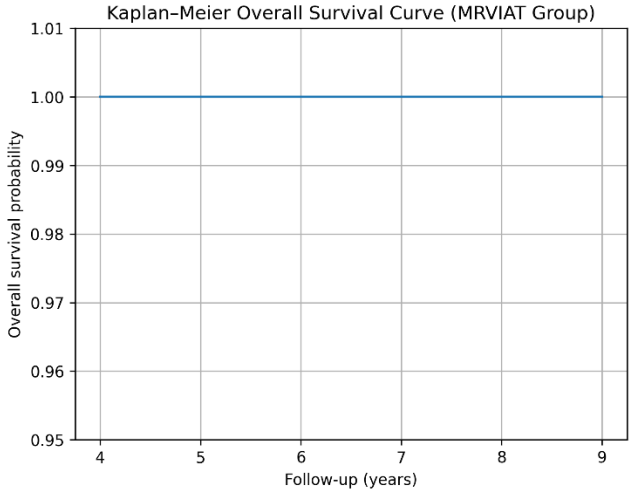


Figure 2. Kaplan–Meier curves for overall survival and freedom from reintervention in the MRVIAT group.

Kaplan–Meier curves demonstrating overall survival and freedom from reintervention following isolated atrial septal defect repair using the mini–right vertical infra-axillary thoracotomy (MRVIAT) approach. During long-term follow-up, no mortality or reintervention events were observed, resulting in a 100% overall survival and reintervention-free rate throughout the study period.

Postoperative mechanical ventilation time was median 0 hours (0–8). The majority of patients were extubated in the operating room. Due to a zero-inflated distribution, non-parametric tests were applied, and a statistically significant difference between phases was observed ($p < 0.001$).

Median ICU length of stay was 18 hours (12–48), and median hospital length of stay was 4 days (2–9).

Safety outcomes

No mortality occurred in the MRVIAT group. No patient required conversion to another surgical approach. Major complications occurred in 3 patients (4.0%): pneumothorax in two patients and wound infection in one patient. All complications were successfully managed using conservative or minimally invasive interventions. No residual shunt,

permanent pacemaker implantation, or reoperation was observed.

Long-term follow-up outcomes

Median follow-up duration in the MRVIAT group was 6.5 years (IQR: 5–8 years; minimum: 4 years; maximum: 9 years). No mortality occurred during follow-up. Early major complications occurred in 3 patients (4%), all of whom remained clinically stable throughout follow-up. No residual shunt, reoperation, or permanent device implantation was recorded. Kaplan–Meier analysis demonstrated a 7-year overall survival rate of 100% in the MRVIAT group. Similarly, freedom from reintervention was 100% during follow-up.

These findings indicate favorable long-term clinical stability in this cohort; however, the absence of mortality and reintervention events limits the discriminatory value of the Kaplan–Meier analysis.

Comparison between MRVIAT and MRALT groups

Comparative results for CPB time, cross-clamp time, mechanical ventilation time, ICU stay, and hospital stay are presented in Table 2. Although CPB and cross-clamp times were significantly shorter in the MRVIAT group, these unadjusted differences should be interpreted cautiously because the groups differed significantly in age, body weight, and body surface area. These comparisons were unadjusted and exploratory and do not imply superiority or equivalence.

CUSUM analysis and learning curve

Learning curves in the MRVIAT group were evaluated using CUSUM curves for total operative time, cardiopulmonary bypass time, and aortic cross-clamp time. The CUSUM curve for total operative time initially demonstrated a positive slope, indicating operative durations above the overall mean and representing the early learning phase. Progressive reduction and transition to a negative slope reflected significant improvement in surgical performance.

Similar trends were observed in CUSUM curves for cardiopulmonary bypass time and aortic cross-clamp time. In all three parameters, a plateau configuration emerged after the transition from positive to negative slope, indicating stabilization of operational efficiency and attainment of technical proficiency.

As the learning process progressed, variability of operative parameters narrowed and outcomes became more consistent. Concordant behavior of all three CUSUM curves supports the presence of a structured and predictable learning process in the MRVIAT technique

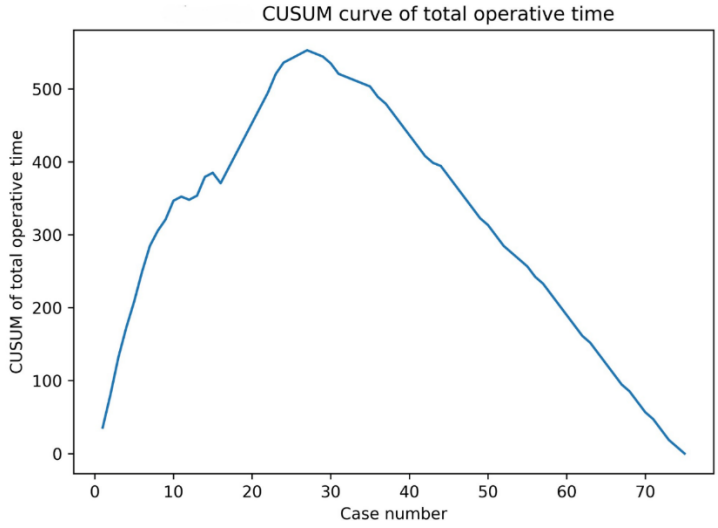


Figure 3. CUSUM curve for total operative time.
The CUSUM curve represents the cumulative deviation of each case from the overall mean operative time. An upward slope indicates operative times above the cohort mean, reflecting the early learning phase. A downward slope indicates operative times below the mean, representing improvement in surgical performance. A plateau pattern reflects stabilization of operative efficiency and achievement of procedural proficiency.

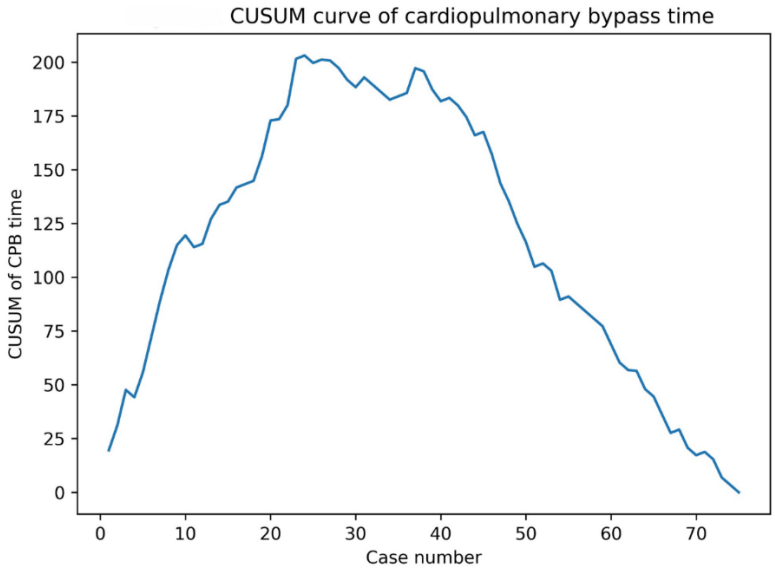


Figure 4. CUSUM curve for cardiopulmonary bypass time.
The CUSUM curve illustrates the cumulative deviation of cardiopulmonary bypass time from the overall mean value. A positive slope corresponds to longer bypass times during the early learning phase, whereas a negative slope indicates improved operative efficiency. A plateau configuration suggests stabilization of cardiopulmonary bypass performance and attainment of technical proficiency.

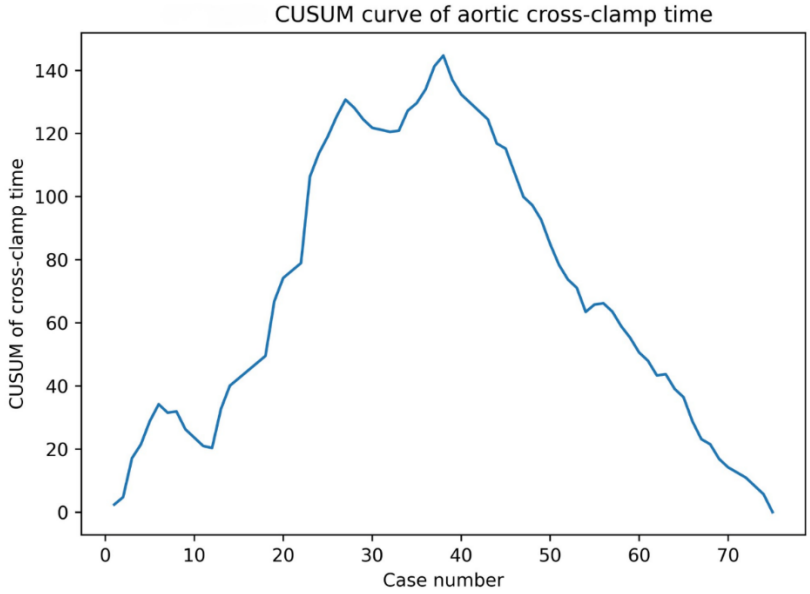


Figure 5. CUSUM curve for aortic cross-clamp time.
The CUSUM curve demonstrates the cumulative deviation of aortic cross-clamp time from the overall mean. An upward slope reflects prolonged cross-clamp durations in the initial learning phase, while a downward slope indicates progressive technical improvement. A plateau trend represents stabilization of surgical performance and completion of the learning curve.

Table 3. Comparison of operative and perioperative outcomes according to learning phases in the MRVIAT group

Variable	Phase I (n=22)	Phase II (n=14)	Phase III (n=39)	p value	η^2 (Effect size)
Total operative time (min), mean ± SD	126.82 ± 16.22	103.93 ± 11.12	91.79 ± 2.69	<0.001	0.328
CPB time (min), mean ± SD	31.64 ± 7.18	23.86 ± 6.76	18.69 ± 5.04	<0.001	0.195
Cross-clamp time (min), mean ± SD	16.23 ± 5.49	16.57 ± 7.73	9.21 ± 3.25	<0.001	0.167
Mechanical ventilation time (h), median (min–max)	5 (0–8)	4 (0–6)	0 (0–6)	<0.001	0.166
ICU stay (h), median (min–max)	24 (16–48)	24 (16–40)	16 (12–48)	0.009	0.031
Hospital stay (days), median (min–max)	4 (2–8)	4.5 (3–5)	4 (3–9)	0.497	—
Major complications, n (%)	2 (9.1)	0 (0)	1 (2.6)	0.320	—

Data are presented as mean ± standard deviation or median (minimum–maximum).
CPB: cardiopulmonary bypass; ICU: intensive care unit; MRVIAT: mini-right vertical infra-axillary thoracotomy; SD: standard deviation; η^2: eta-squared effect size.
Post-hoc pairwise comparisons were performed using Bonferroni-corrected Mann–Whitney U tests (significance level $p < 0.017$).

Phase-based comparisons (Phase I–II–III)

Operative and perioperative outcomes by phase are summarized in Table 3

Operative times

Total operative time decreased from 126.82 ± 16.22 minutes in Phase I to 103.93 ± 11.12 minutes in Phase II and 91.79 ± 2.69 minutes in Phase III ($p < 0.001$). Effect size was large ($H=36.41$; $\eta^2=0.328$). Cardiopulmonary bypass time was 31.64 ± 7.18, 23.86 ± 6.76, and 18.69 ± 5.04 minutes in Phases I, II, and III, respectively ($H=22.44$; $p<0.001$; $\eta^2=0.195$). Aortic cross-clamp time was 16.23 ± 5.49, 16.57 ± 7.73, and 9.21 ± 3.25 minutes, respectively ($H=19.54$; $p<0.001$; $\eta^2=0.167$).

Perioperative outcomes

Mechanical ventilation time decreased progressively (Phase I: 5 h [0–8]; Phase II: 4 h [0–6]; Phase III: 0 h [0–6]; $H=19.39$; $p<0.001$; $\eta^2=0.166$). ICU stay decreased modestly across phases (24 h [16–48], 24 h [16–40], 16 h [12–48]; $H=5.31$; $p=0.009$; $\eta^2=0.031$). Hospital stay did not differ significantly between phases ($p=0.497$).

Bonferroni-corrected Mann–Whitney U tests showed:

- Total operative time: significant for Phase I vs III ($p<0.001$) and Phase II vs III ($p=0.002$).
- CPB time: significant for Phase I vs III ($p=0.003$) and Phase II vs III ($p=0.008$).
- Cross-clamp time: significant only for Phase II vs III ($p=0.002$).
- Mechanical ventilation time: significant for Phase I vs III ($p=0.007$) and Phase II vs III ($p<0.001$).
- ICU and hospital stay: no Bonferroni-corrected significant differences.

Safety Profile

Major complication rates were 9.1% in Phase I, 0% in Phase II, and 2.6% in Phase III ($p=0.320$). No conversion occurred in any phase.

Multivariable Analysis of Operative Time

There was no significant correlation between case order and body surface area (Spearman $\rho = -0.186$, $p = 0.110$), indicating no statistically significant temporal trend in patient size across the learning period. In multivariable linear regression analysis, case order remained independently associated with reduced operative time after adjustment for body surface area, closure type, and sex.

Each incremental case was associated with a significant reduction in operative duration ($\beta = -0.62$ minutes per case; 95% CI −0.73 to −0.51; $p < 0.001$)

Table 4. Multivariable linear regression analysis of operative time (MRVIAT cohort, n = 75)

Variable	β (Minutes)	95% Confidence Interval	p-value	VIF
Case order (per case)	−0.62	−0.73 to −0.51	<0.001	1.03
Body surface area (m²)	0.89	−5.41 to 7.19	0.780	1.05
Patch closure (yes vs no)	12.58	7.67 to 17.50	<0.001	1.02
Male sex (vs female)	0.83	−3.87 to 5.53	0.726	1.04

Dependent variable: Total operative time (minutes).
Model $R^2 = 0.714$; Adjusted $R^2 = 0.698$.
VIF: variance inflation factor; MRVIAT: mini-right vertical infra-axillary thoracotomy.
Multivariable linear regression analysis demonstrating the independent association between cumulative surgical experience (case order) and total operative time after adjustment for body surface area, closure type, and sex. Variance inflation factor (VIF) values indicate absence of significant multicollinearity.

Patch closure independently prolonged operative time, whereas body surface area and sex were not significant predictors. These findings suggest that the improvement in operative efficiency was independently associated with accumulated surgical experience after adjustment for measured patient characteristics; however, residual selection bias cannot be excluded.

Segmented regression analysis demonstrated that operative time decreased steeply up to case 22, after which the slope significantly flattened, indicating transition from rapid skill acquisition to consolidation phase. When case 38 was tested as breakpoint, slope reduction after this threshold approached zero, consistent with performance stabilization.

Table 5. Segmented regression analysis for breakpoint validation (MRVIAT cohort, n = 75)

Breakpoint (Case No.)	Pre-breakpoint Slope β (minutes/case)	Post-breakpoint Slope β (minutes/case)	Slope Change (β_2)	p-value (Slope Change)
22	−1.34	−0.40	+0.94	0.012
38	−1.14	−0.04	+1.10	<0.001

Model description:
Dependent variable: Total operative time (minutes)
Covariates: Body surface area, closure type, sex
MRVIAT: mini-right vertical infra-axillary thoracotomy; CUSUM: cumulative sum.
Segmented (piecewise) linear regression analysis evaluating candidate breakpoints derived from CUSUM slope inflection. The 22-case breakpoint reflects rapid early performance improvement followed by slower decline in operative time, whereas the 38-case breakpoint demonstrates near-zero post-slope consistent with performance stabilization. The 22-case breakpoint was interpreted as the functional proficiency threshold, whereas the 38-case breakpoint was interpreted as the performance stabilization threshold.

These mathematical findings supported the CUSUM-derived identification of approximately 22 cases for functional proficiency and 35–40 cases for performance stabilization. The mathematical validation of the CUSUM-derived inflection points using segmented regression is presented in Supplementary Figure 2.

Eta-squared values demonstrated large effect sizes for operative time, CPB time, cross-clamp time, and mechanical ventilation time ($\eta^2 \geq 0.14$). ICU stay showed a small effect size (η^2=0.031). Hospital stay and major complication rates demonstrated no meaningful effect size.

DISCUSSION

CUSUM curves derived from total operative time, cardiopulmonary bypass time, and aortic cross-clamp time demonstrated a clear and consistent improvement in performance throughout the learning process of the MRVIAT technique. The initial positive slope observed in these curves corresponds to the early learning phase described in previous studies on minimally invasive cardiac surgery learning curves, reflecting operative durations above the reference mean. In the literature, this phase has been characterized by prolonged operative times related to limited surgical exposure and the need for ergonomic adaptation[10,11].

The subsequent transition from a positive to a negative slope, followed by a plateau configuration across all three parameters, indicates stabilization of operational efficiency and attainment of technical proficiency. This plateau pattern is consistent with previously reported learning curve models for MRVIAT and similar minimally invasive approaches and suggests that the learning process is completed not only through acceleration but also through consolidation of performance consistency[13,14].

The concordant slope changes observed in three independent operative parameters further support that the learning process is structured and predictable rather than random. As emphasized in the literature, defining phase boundaries based on multiparametric performance indicators rather than a single variable provides a more robust and methodologically reliable framework for learning curve assessment[10].

Based on these findings, functional surgical proficiency in the MRVIAT technique appears to be achieved after approximately 22 cases, while operational performance enters a stabilization phase after 35–40 cases. When compared with learning thresholds reported for minimally invasive cardiac surgery in previous studies, these case numbers fall within clinically realistic and consistent ranges[15-18]. Accordingly, CUSUM analysis enables objective, reproducible, and literature-concordant definition of a learning threshold for the safe clinical integration of the MRVIAT approach.

Importantly, the independent association between case order and operative time in adjusted regression analysis strengthens the validity of the learning curve interpretation. Moreover, segmented regression mathematically confirmed the slope inflection points identified by CUSUM analysis, demonstrating a rapid early learning phase followed by performance stabilization. This combined analytical approach provides a more robust framework than descriptive time-based assessment alone.

The progressive reduction in total operative time, cardiopulmonary bypass time, and aortic cross-clamp time across learning phases indicates a continuous improvement in surgical fluency and technical mastery. This parallel improvement pattern closely aligns with prior learning curve studies in minimally invasive cardiac surgery. Despite limited operative exposure and ergonomic constraints, previous reports consistently demonstrate a marked and sustained shortening of operative times with increasing experience[19]. Our results confirm that the learning process in MRVIAT is characterized not merely by theoretical adaptation but by directly measurable operational gains, supporting the rapid enhancement of surgical efficiency and clinical applicability.

The significant reduction in mechanical ventilation time in later phases and the high proportion of patients extubated in the operating room indicate that the learning process extends beyond operative parameters and directly influences early postoperative recovery dynamics. The statistical significance driven by a distributional shift toward early extubation rather than median differences is consistent with previously described fast-track recovery patterns after minimally invasive cardiac surgery[20].

In contrast, although ICU length of stay showed statistical significance across phases, the small effect size suggests limited clinical relevance. Similarly, previous learning curve studies have reported that ICU duration is often influenced more by patient characteristics and institutional protocols than by surgical experience alone[21].

The absence of significant differences in hospital length of stay between phases further supports that the MRVIAT approach maintains an acceptable safety profile even during early learning stages and does not lead to prolonged hospitalization. Collectively, these findings demonstrate that the learning process in MRVIAT contributes in a balanced manner to both surgical performance and early postoperative recovery.

One of the important strengths of this study is the evaluation of learning curves not only through p values but also through effect size metrics. The large effect sizes observed for operative time, cardiopulmonary bypass time, cross-clamp time, and mechanical ventilation time indicate that the learning curve exerts not only statistical but also clinically meaningful impact. This confirms that experience gained during MRVIAT training translates into tangible clinical outcomes[10,22].

Comparisons with the MRALT group were interpreted as exploratory because of demographic imbalances between groups. Accordingly, this study does not aim to establish superiority or equivalence between surgical approaches. Nevertheless, the similarity of early clinical outcomes supports the feasibility of MRVIAT as a safe alternative in appropriately selected patients. In this context, the

MRALT group served as a contextual comparator among minimally invasive thoracotomy approaches rather than as a benchmark against sternotomy.

The predominance of major complications in the early learning phase underscores the importance of the learning curve concept for clinical safety. The low complication rates observed in later phases suggest a possible reduction in surgical risk with increasing experience. These findings highlight the necessity of structured training and stepwise implementation strategies when initiating MRVIAT programs in new centers[4,19].

A major strength of this study is the long median follow-up duration of approximately seven years. While early outcomes of minimally invasive approaches are frequently reported, data regarding late clinical stability, residual shunt, reintervention, and functional outcomes remain limited. In this regard, our long-term follow-up demonstrates not only early safety but also durable clinical effectiveness of the MRVIAT technique. The absence of residual shunt, reoperation, or major late cardiac complications supports MRVIAT as a reliable surgical option for long-term outcomes as well[4,16,17].

Studies focusing on the learning curve of MRVIAT remain scarce, and most do not quantitatively define phase transition points. Therefore, our CUSUM-based phase analysis provides an original contribution by objectively quantifying learning progression. In particular, identification of functional proficiency after approximately 22 cases offers a practical benchmark for surgeons and centers initiating MRVIAT programs[5,18-23].

Several limitations should be acknowledged. This study is retrospective and single-center in design. All procedures were performed by a single surgeon, which limits generalizability and reflects an individual rather than institutional learning curve. The MRVIAT group also included patients with higher age, body weight, and body surface area, suggesting possible selection bias during early learning phases toward anatomically favorable cases. The limited sample size may have reduced statistical power for complication analyses. Additionally, the absence of events limited the discriminatory capacity of Kaplan–Meier analysis. Nevertheless, the homogeneous patient cohort, long follow-up duration, and CUSUM-based analytical approach strengthen the methodological robustness of this study.

CUSUM analysis demonstrated that, in this single-surgeon series, functional surgical proficiency was observed after approximately 22 cases, while operational performance stabilized after 35–40 cases. These values represent an individual learning trajectory and should not be interpreted as universal institutional thresholds. These findings indicate that the learning process of MRVIAT is predictable and manageable, offering a realistic framework for training and patient selection. Accordingly, this study demonstrates that the MRVIAT approach is not only technically feasible but can also be safely integrated into clinical practice through a controlled and structured learning process.

Future studies should validate these learning thresholds in larger, multicenter cohorts involving multiple surgeons with different levels of experience. Prospective studies incorporating standardized patient selection criteria and risk-adjusted learning curve analyses may help determine whether the approximately 22-case proficiency threshold and 35–40-case stabilization period observed in this series are reproducible across different institutions. Larger cohorts are also needed to more reliably evaluate the relationship between increasing surgical experience and infrequent adverse clinical outcomes.

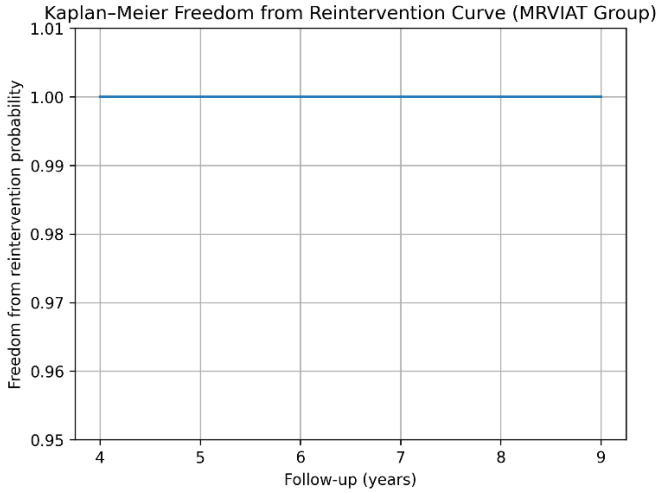
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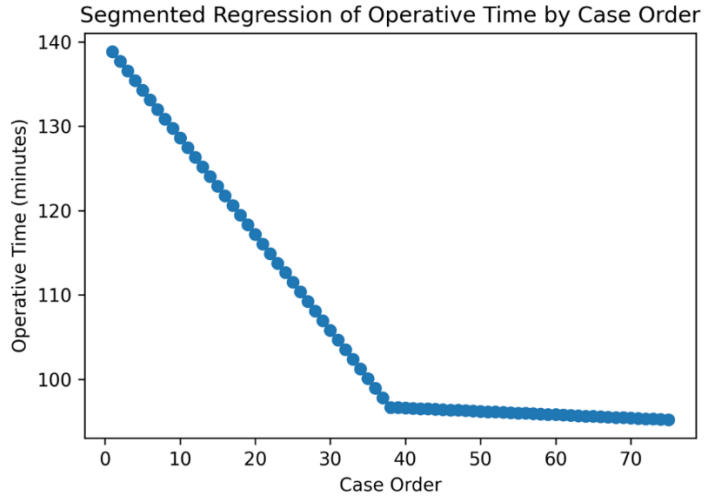
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ADDENDUM. SUPPLEMENTARY FIGURES



Supplementary Figure 1. Freedom from reintervention after MRVIAT repair.
Kaplan–Meier curve showing freedom from reintervention in patients undergoing isolated atrial septal defect repair via the mini–right vertical infra-axillary thoracotomy (MRVIAT) approach. No reintervention events occurred during the follow-up period, resulting in a 100% freedom from reintervention rate.



Supplementary Figure 2.
Segmented (piecewise) linear regression model of total operative time according to case order in the MRVIAT cohort. The model demonstrates a steep early decline in operative time followed by slope flattening consistent with performance stabilization after the identified breakpoint.