The advantage of early plication in children diagnosed with diaphragm paresis

Alejandro A. Floh, MD, MSc,^a Intikhab Zafurallah, MD,^b Cathy MacDonald, MD,^c Osami Honjo, MD, PhD,^d Chun-Po S. Fan, PhD, PStat,^e and Peter C. Laussen, MB, BS^f

ABSTRACT

Background: In this single-center study, we sought to determine the frequency of phrenic nerve injury leading to diaphragm paresis (DP) in children following open cardiac surgery over the last 10 years, and to identify possible variables that predict the need for plication and associated clinical outcomes.

Methods: Patients diagnosed with DP were identified from departmental databases and a review of clinical diaphragm ultrasound images. A cohort was analyzed for predictors of diaphragm plication and associations with clinical outcomes. Cumulative proportion graphs modeled the association between plication and length of stay.

Results: DP was diagnosed in 161 of 6448 patients (2.5%) seen between January 2002 and December 2012. All diagnoses but 1 were confirmed by ultrasound. Plication of the diaphragm was performed in 30 patients (19%); compared with patients who did not undergo plication, these patients were younger (median age, 10 days vs 138 days; $P < .001$), more likely to have undergone deep hypothermic circulatory arrest (47% vs 18%; $P = .005$), had a longer duration of positive pressure ventilation (median, 15 days vs 7 days; $P < .001$), and had longer lengths of stay in both the intensive care unit (median, 23 days vs 8 days; $P < .0001$) and the hospital (median, 37 days vs 15 days; $P < .0001$). Early plication was associated with reduction in all intervals of care.

Conclusions: Early plication should be considered for patients with diaphragm paresis requiring prolonged respiratory support after cardiac bypass surgery. Longer follow-up evaluation is required to better define the long-term implications of plication. (J Thorac Cardiovasc Surg 2017;154:1715-21)

Cumulative proportion of intensive care unit discharge from index operation according to time to plication.

Central Message

Neonates with diaphragm paresis are at risk for requiring diaphragm plication. Early plication for those dependent on respiratory support facilitates weaning off ventilation and shortens intensive care unit and hospital lengths of stay.

Perspective

Diaphragm paresis (DP) occurs following pediatric cardiac surgery. Neonatal age and the use of deep hypothermic circulatory arrest are the strongest predictors of requiring plication to separate from respiratory support. Delays in plication result in prolonged intensive care unit and hospital stays. Routine follow-up is needed to define the natural history of DP and plication.

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From the ^aDepartment of Critical Care Medicine and Labatt Family Heart Centre, Departments of ^cRadiology and ^fCritical Care Medicine, ^dDivision of Cardiovascular Surgery and Labatt Family Heart Centre, and ^eCardiovascular Data Management Centre, The Hospital for Sick Children, Toronto, Ontario, Canada; and ^bPaediatric Intensive Care and KIDS Retrieval Service, Birmingham Children's Hospital, Birmingham, United Kingdom.

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Address for reprints: Alejandro A. Floh, MD, MSc, The Hospital for Sick Children, 555 University Ave, Toronto, Ontario, Canada M5G 1X8 (E-mail: alejandrofloh@sickkids.ca).

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Phrenic nerve injury resulting in diaphragmatic paresis (DP) has a reported frequency of 3% to 12.8% after pediatric cardiac surgery.¹⁻⁴ Associated perioperative morbidity includes increased duration of mechanical

Scanning this QR code will take you to supplemental figures and tables for this article.

Abbreviations and Acronyms

CPB	= cardiopulmonary bypass
DHCA	= deep hypothermic circulatory arrest
DP	= diaphragm paresis
ICU	= intensive care unit
IQR	= interquartile range

ventilation, increased risk of atelectasis and pulmonary infection, prolonged postoperative recovery, increased length of stay in the intensive care unit (ICU), and increased hospitalization costs.^{5,6}

The diagnosis of DP is suspected clinically in the context of increased work of breathing, persistently elevated hemidiaphragm (on roentgenogram), and failure to separate from positive-pressure ventilation. Diaphragmatic movement can be further evaluated using fluoroscopy and ultrasonography. Management strategies for DP range from supportive care with continued ventilator support while awaiting recovery of function to diaphragm plication to improve respiratory mechanics. Indications for surgical intervention are highly variable, with a tendency toward early plication seen in some centers, especially in infants.⁷

The purpose of this study was to identify the incidence of and risk factors for DP, and to examine the variability in management of DP following cardiac surgery. We also sought to describe the impact of diaphragm plication on intervals of care, including duration of ventilation and length of ICU and hospital stay.

METHODS

We conducted a retrospective review of all patients admitted to the cardiac intensive care unit of The Hospital for Sick Children, Toronto, after pediatric cardiac surgery between January 2002 and December 2012 who were diagnosed with DP. This study was approved by the hospital's Research Ethics Board, with a waiver of the requirement for consent. Subjects with DP and subjects who had undergone diaphragm plication were identified from the cardiology, cardiovascular surgery, and critical care databases. To ensure that potential subjects were not missed because of coding errors, charts of all patients who underwent ultrasound evaluation of diaphragm function and had previous cardiac surgery were identified from the radiology database and reviewed by a member of the research team (I.Z.). Subjects were included in the analysis if DP was diagnosed following the index surgery but within the index hospitalization. Subjects were excluded who had preoperative evidence of an elevated hemidiaphragm, known diagnosis of neuromuscular disease, or ventilator dependence (either invasive or noninvasive). No subjects were excluded for preoperative diaphragm elevation.

The management of patients identified with DP was left to the discretion of the responsible medical and surgical team. A standardized treatment protocol was not in place, but plication was generally considered for patients who failed multiple extubation attempts or were unable to wean from positive-pressure ventilation. All surgical plications were completed through a standardized approach. A thoracotomy at the level of the fifth or sixth intercostal space was used to mobilize the ipsilateral lung and divide the inferior pulmonary ligament. Several 4-0 polypropylene sutures (Polene; Ethicon, Somerville, NJ) with Teflon pledgets were placed to plicate the diaphragm into a flat position with some tension.

Demographic data, cardiac anatomy, cardiac surgery, additional interventions, and intervals of care were extracted from the electronic medical records. The time of DP diagnosis was defined as the time of confirmatory testing, including diaphragm ultrasound or fluoroscopy, or the time of index surgery if direct dissection of phrenic nerve was observed. DP was defined as minimal, absent, or paradoxical movement of the diaphragm as reported on confirmatory testing. Absent or diminished diaphragm movement in the proper direction was defined as paresis; diaphragms with paradoxical motion were considered paralyzed.

The primary outcome was total duration of positive pressure ventilation support, including all periods in which invasive and noninvasive support (continuous positive airway pressure/bilevel positive airway pressure) was provided. The durations of ICU stay and hospital stay were evaluated as secondary endpoints.

All continuous variables are expressed as mean $\pm$ standard deviation or median with interquartile range (IQR) according to their distribution. Categorical data are expressed as frequencies and proportions. The incidence of DP was defined as the number of identified cases by the total number of cardiac surgeries over the corresponding time period. Patients who underwent plication were categorized as early plication (<7 days after DP diagnosis) or late plication (≥ 7 days after DP diagnosis). Seven days was chosen as the clinical limit by which time most of the other perioperative causes of ongoing respiratory support would have been resolved or addressed. Univariate linear regression was used to identify the direction and strength of associations between risk factors, surgical diaphragm plication, and outcomes. Owing to the competing event of postoperative mortality, the primary and secondary outcome variables were analyzed using competing-risk models. Cumulative incidence functions were used to model hospital discharge from the index operation, comparing patients who underwent diaphragm plication versus those who did not, and those who underwent earlier plication versus those who underwent later plication. Between-group differences were assessed using Gray's test. The competing-risk models were also used to summarize the median (IQR) of the time-to-event variables. Subgroup analysis included cumulative incidence functions to explore the association between the timing of plication and the time to discharge from plication surgery. All statistical analyses were performed using SAS version 9.3 (SAS Institute, Cary, NC). A *P* value $\leq .05$ was considered statistically significant.

RESULTS

A diagnosis of DP was identified in 161 patients, 4 of whom were diagnosed after hospital discharge and thus were excluded from this analysis. A total of 6448 index open cardiac operations were completed during this time interval, corresponding to an overall incidence of DP of 2.4%. DP was diagnosed at a median of 7 days (IQR, 4-12 days) after surgery. Ultrasound was the primary confirmatory imaging modality in all but 1 case, with the diagnosis confirmed on visual inspection in only a single subject. Diaphragm plication was completed in 30 patients (19%).

Demographic Data

The study population was predominately male (63%), with a median age of 84 days (IQR, 9-310 days). The majority had undergone biventricular heart surgery (74%). Infants composed 76% (*n* = 12) of the cohort. The surgical approach was median sternotomy in 94% of the patients, and 88% of the surgeries used cardiopulmonary bypass (CPB). The most common surgical procedures included

TABLE 1. Demographic data

Clinical characteristics	With plication (n = 30)	Without plication (n = 127)	P value
Age, d, median (IQR)	10 (6-47)	138 (11-682)	<.001
Male sex, n (%)	20 (67)	79 (62)	.68
Ventricular physiology, n (%)			.36
Univentricular	10 (33)	31 (24)	
Biventricular	20 (67)	97 (76)	
RACHS score, n (%)			.35
1	0 (0)	4 (3)	
2	5 (17)	37 (29)	
3	11 (37)	48 (38)	
4	10 (33)	24 (19)	
5	3 (10)	7 (5)	
Missing	1 (3)	8 (6)	
Median sternotomy, n (%)	28 (93)	121 (95)	.68
Previous surgery, n (%)	6 (20)	37 (29)	.37
CPB time, min, mean $\pm$ SD	148 $\pm$ 50	137 $\pm$ 63	.33
Cross-clamp time, min, median (IQR)	133 (117-178)	127 (99-157)	.19
Use of DHCA, n (%)	14 (47)	23 (18)	.005
Diaphragm activity, n (%)			.005
Paresis	12 (40)	89 (70)	
Paralysis	18 (60)	37 (29)	
Missing	0 (0)	2 (2)	
Mode of diagnosis, n (%)	29 (97)	128 (100)	.19
Ultrasound	29 (97)	128 (100)	
Direct	1 (3)	0 (0)	
Invasive ventilation at diagnosis, n (%)	29 (97)	125 (98)	.57
Noninvasive ventilation following diagnosis, n (%)	17 (59)	47 (38)	.12
Total days on PPV, median (IQR)	15 (9-30)	7 (3-12)	<.001
ICU length of stay from index surgery, d, median (IQR)	27 (20-45)	8 (5-16)	.0022
ICU length of stay following plication, d, median (IQR)	3 (2-9)		
Hospital length of stay from index surgery, d, median (IQR)	37 (30-57)	16 (10-35)	.066
Hospital length of stay following plication, d, median (IQR)	11 (8-26)		

IQR, Interquartile range; RACHS, risk adjustment for congenital heart surgery; CPB, cardiopulmonary bypass; DHCA, deep hypothermic circulatory arrest; PPV, positive-pressure ventilation; ICU, intensive care unit.

operations requiring arch repair (13%), repair of Tetralogy of Fallot or right ventricular outflow tract obstruction (10%), and the arterial switch operation (9%) (Table E1). The most common operations in children aged >1 year included the Fontan procedure (n = 7), heart transplantation and repair of Tetralogy of Fallot (each n = 5), and arch repair (n = 4).

Diaphragm Plication

Plication was performed at a median of 6 days (IQR, 2-21 days) after diagnosis. Compared with patients without plication, those undergoing plication were younger (median age, 10 days [IQR, 6-47 days] vs 138 days [IQR, 11-682 days]; $P < .001$) and had undergone deep hypothermic circulatory arrest (DHCA; 14 [47%] vs 23

FIGURE 1. Cumulative proportions of patients discharged from the ICU since the index operation in patients with no plication versus those with plication (A) and patients with early versus late versus no plication (B). *ICU*, Intensive care unit.

[18%]; $P = .005$) (Table 1). There was an association between diaphragm paralysis and plication, seen in 18 of 30 patients who underwent plication (60%) versus 37 of 127 patients who did not undergo plication (29%) ($P = .005$). Otherwise both groups had similar operative

and diagnostic profiles. The interval from the index operation to diagnosis was longer in patients who underwent plication compared with those who did not (median, 9 days [IQR, 6-17 days] vs 6 days [IQR, 3-11]; $P = .02$). The median time from DP diagnosis to plication was 18 days (IQR, 11-28 days), with 53% ($n = 16$) receiving early plication and 47% ($n = 14$) receiving late plication. In a subgroup analysis, patients undergoing early plication and those undergoing late plication had similar demographic data and surgical complexity, but the former were more likely to have diaphragmatic paralysis than paresis.

Patients were discharged from the ICU at a median of 3 days (IQR, 2-9 days) after surgical plication, and from the hospital at a median of 11 days (IQR, 8-26 days) (Table E2). The times to ICU and hospital discharge after plication did not vary by timing (earlier vs later) of plication ($P = .78$ for hospital discharge; $P = .59$ for ICU discharge) (Figure 1).

The likelihood of undergoing diaphragm plication was highest during the neonatal period and decreased progressively with increasing age (Figure 2). Age and use of DHCA were the only 2 factors associated with plication (Table E3). Nevertheless, 42 neonates with DP were successfully discharged without undergoing plication. These neonates were similar to the neonates who required plication in all predictors except use of DHCA, which was used in 12 of 21 neonates who received plication (57%) versus 13 of 42 neonates who did not undergo plication (31%) ($P = .05$).

FIGURE 2. Probability of undergoing plication by age in patients diagnosed with DP.

FIGURE 3. Cumulative proportions of patients discharged from the ICU (A) and from the hospital (B) in patients with early versus late plication. ICU, Intensive care unit.

Ventilation Requirements and Intervals of Care

At the time of DP diagnosis, 155 of 157 patients were receiving positive pressure ventilation. Patients who underwent plication of the diaphragm had a longer total duration of positive pressure (invasive and noninvasive) ventilation (median, 15 days [IQR, 9-30 days] vs 7 days [IQR, 3-12 days]; $P < .001$), longer ICU stay (median, 23 days [IQR, 18-42 days] vs 8 days [IQR, 5-17 days]; $P < .0001$), and longer hospital stay (median, 37 days [IQR, 30-57 days] vs 15 days [IQR, 10-34 days]; $P < .0001$).

An ordinal relationship was found between the duration of ventilation and timing of plication. Patients undergoing earlier plication had a longer total duration of ventilation compared with those without plication (median, 10 days [IQR, 7-14 days] vs 7 days [IQR, 3-12 days]; $P = .03$), but shorter than those undergoing late plication (median, 10 days [IQR, 7-14 days] vs 30 days [IQR, 22-39 days]; $P < .001$). Cumulative incidence analysis revealed similar associations between the timing of plication and ICU length of stay (Figure 3) and hospital length of stay (Figure E1). These figures also demonstrate that following plication, there was no difference in the subsequent trajectory for recovery as measured by length of stay when compared to patients who did not need plication. The difference in hospital length of stay between early and late plication disappeared when referenced to late plication (Figure 1).

Patients Not Undergoing Plication

Diaphragm plication was not performed in 131 patients diagnosed with DP, 37 (29%) of whom had complete

paralysis. Nearly all (99%) were on ventilator support the day of DP diagnosis, but only 41% required ongoing respiratory support thereafter (Table 1). Respiratory support was provided for a median of 7 days (IQR, 3-12 days) in this group. The times to ICU and hospital discharge were similar for patients with paralysis and those with diaphragm paresis (Figure E2).

Long-Term Follow-up

Patients with DP did not undergo consistent follow-up evaluation. Repeat imaging was available for all but 4 patients at a median follow-up of 175 (18-1255) days. The respective median follow-up for patients with and without plications was 319 (59-936) and 141 (17-1259), respectively, and was not statistically significant ($P = .22$). The affected diaphragm was in an elevated position in 6 patients (20%) who underwent plication and in 57 (45%) who did not.

DISCUSSION

In this single-center retrospective study, the incidence of DP following pediatric cardiac surgery was in range of that reported from other studies, and the need for diaphragm plication was more likely in neonates and patients who had undergone DHCA. The timing or indications for plication are not well defined, but we demonstrate the advantage of earlier plication in reducing the intervals of care for these patients.

DP after cardiac surgery results in altered respiratory mechanics that can lead to respiratory distress and

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prolonged ventilation support.² Affected patients with DP may be supported with positive-pressure ventilation for a longer period in the hope of functional recovery and the avoidance of further surgery; however, recovery is unpredictable, and prolonged ICU admission can expose these fragile patients to additional risk and morbidity.³ Plication of the affected diaphragm can improve the work of breathing and facilitate separation from positive-pressure support.⁸ This variability in clinical condition also leads to variability and uncertainty when trying to determine the best management strategy at the individual patient level. This study demonstrates that surgical plication targeted to high-risk patients can modify their clinical trajectory, leading to earlier extubation and shorter ICU and hospital lengths of stay, more in the range of those values seen in lower-risk patients.

For patients who ultimately underwent plication, delays in DP diagnosis and the time interval between diagnosis of DP and surgical plication had significant impacts on intervals of care. The patients who underwent plication spent more time on positive-pressure support and had longer ICU and hospital lengths of stay; this reflects a delay in DP diagnosis (by 3 days on average in these patients), and a median interval of 18 days between diagnosis and plication. After plication, the intervals of care were reduced. This was best demonstrated by the cumulative proportion curves for the patients who underwent plication and those who did not (Figure E1). When analyzed as a single group, the cumulative proportions curve of hospital discharge for patients with DP who underwent plication paralleled that of the patients who did not undergo plication but shifted to the right. However, when analyzed separately, patients undergoing early plication (within 7 days of DP diagnosis) had similar ICU and hospital discharge times as those who did not receive plication surgery. A wide and significant separation was seen in the patients undergoing later plication compared with those undergoing earlier or no plication. This separation disappeared when the discharge was reference to time of diaphragm plication and not time of surgery (Figure 1), suggesting that although DP requiring plication has been identified as an independent predictor associated with a 4-fold increase in hospital length of stay,⁹ these findings support the idea that rapid transition to diaphragm plication actually may promote earlier discharge and less resource utilization.

The indications for diaphragm plication in our patients were not captured, and we did not have a standardized care pathway for management of DP. Comparing our current series of patients with a historical cohort from our institution,³ the median time to DP diagnosis was largely unchanged, but the median interval from DP diagnosis to plication was shortened by 11 days. In another older study of diaphragm plication following phrenic

nerve injury, successful separation from ventilation support was possible within 24 hours.¹⁰ Our approach to treating DP has typically been to defer either extubation attempts or plication until the patient's clinical state has been optimized to the degree possible; however, our present data suggest that this approach may be unnecessary and indeed may delay catch-up in the trajectory of recovery.

We found that age was one of the strongest predictors for plication, with neonates who failed to separate from mechanical ventilation undergoing plication surgery. This is not surprising, given that the phrenic nerve injury during cardiac surgery leading to DP has a significant impact on respiratory mechanics in newborns and infants in particular.¹¹ The higher chest wall compliance in these patients results in a lower functional reserve volume. When paretic or paralyzed, the diaphragm sits higher and reduces lung volume and expansion on that side. This in turn is associated with atelectasis, increased risk of hypoxemia from a reduction in oxygen reserve capacity, and an increase in the work of breathing. Furthermore, the diaphragm is the main muscle of respiration, and becomes readily fatigued. The need for diaphragm plication has been associated with younger age in other studies,^{2,3,7} but the median age of 10 days (IQR, 6-47 days) in our population is far younger than published previously. It also is important to note that not all of our neonates with DP required plication; approximately 33% (n = 42) of all patients discharged without undergoing plication were under 30 days of age. Despite a similar demographic profile, these patients had an additional respiratory reserve not seen in the others. Their successful separation from respiratory support might be explained by the fact that these patients were stronger, better nourished, and without residual lesions; however, these data elements were not captured, and further assessment is needed, primarily in neonates. Consistent with previous reports,¹² plication was rare in older infants and children.

The clinical impact of a paralyzed diaphragm demonstrating paradoxical inspiratory motion is often considered greater in those that are paretic with minimal or no movement.⁷ In this study, paralysis was more common in the patients who underwent plication, especially in those who underwent early plication (Table E2). Nevertheless, this difference in diaphragm motion had no impact on the time to hospital discharge. This suggests that the position of the diaphragm, not the movement of the diaphragm, may be the critical component. A diaphragm sitting higher in the thorax will cause a loss of lung volume and alter respiratory mechanics.

Despite the recognized benefits of plication, there is occasional reluctance to perform this surgery because of the surgical risk and inconsistent success. Surgical plication effectively lowers the position of the diaphragm and allows for lung expansion, but does not enhance the recovery of

diaphragm function. The plication may be ineffective, and the diaphragm may rise into the thorax once again until the diaphragm has been reinnervated. The natural and modified history of DP is largely unknown, with data limited to small retrospective studies all using varying modes of evaluation.^{10,13} Tonz and colleagues reported that 75% of patients without plication and >90% of those with plication had a normal diaphragm position on X-ray.¹³ In a separate study, of the 95% of patients who showed an element of functional recovery by 8 years after diaphragm plication, only 50% had >75% of normal excursion.¹¹ Standardized surveillance was not established in our institution, and the return of function for this cohort was not known.

This study has some limitations that need to be considered. First, inclusion into the study was based on a clinical diagnosis of DP. Ultrasound and, in other institutions, fluoroscopy are undertaken in patients with high suspicion. It is possible that some patients with DP escaped diagnosis because of an uneventful recovery and failure to identify an elevated hemidiaphragm on chest X-ray. These patients would not have been captured by our extended search criteria. Second, the study's retrospective nature precluded us from evaluating the rationale behind decision making for plication. As such, there may be inherent biases that could not be addressed. Finally, the relatively low frequency of diaphragm plication over the last 10 years (31 cases) increases the risk of insufficient power for analysis and introduction of type II (beta error). A larger multicenter study is needed to better clarify the potential relationship between predictors and plication.

CONCLUSIONS

DP is a complication of pediatric cardiac surgery that can result in prolonged ventilation. Younger patients with a decreased respiratory reserve are more likely to not tolerate DP and to require additional intervention. Early diaphragm

plication may be preferable to reduce ICU and hospital lengths of stay.

Conflict of Interest Statement

Authors have nothing to disclose with regard to commercial support.

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Key Words: cardiac surgery, diaphragm paresis, Pediatrics, plication

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FIGURE E1. Cumulative proportions of patients discharged from the hospital since the index operation comparing no plication versus plication (A) and early versus late versus no plication (B). *ICU*, Intensive care unit.

FIGURE E2. Cumulative proportions of patients with diaphragm paresis versus paralysis who did not undergo plication discharged from the ICU (A) and hospital (B) since the index operation. *ICU*, Intensive care unit.

TABLE E1. Types of operations

Operation type	All patients	Patients aged <1 y
Arch repair, VSD/arch repair, coarctation repair	20 (13)	16 (13)
TOF/RVOTO repair	16 (10)	11 (9)
Arterial switch operation	15 (9)	14 (11)
Bidirectional cavopulmonary shunt	11 (7)	11 (9)
Arterial switch/VSD closure	10 (6)	10 (8)
Atrioventricular septal defect repair	10 (6)	9 (7)
Stage 1 single ventricle palliation	9 (6)	9 (7)
Heart transplantation	8 (5)	3 (2)
Truncus arteriosus repair	8 (5)	8 (7)
Fontan operation	7 (4)	
Sutureless pulmonary vein repair	7 (4)	7 (6)
Right ventricular–pulmonary artery conduit replacement	6 (4)	3 (2)
Blalock–Taussig shunt	6 (4)	6 (5)
VSD closure	5 (3)	4 (3)
Atrial septal defect closure	4 (3)	
Pulmonary artery banding	4 (3)	4 (3)
Left ventricular outflow tract obstruction	3 (2)	2 (2)
Mitral valve repair	3 (2)	
Unifocalization	2 (1)	1 (1)
Other	2 (1)	
Double switch operation	1 (1)	
Tricuspid valve repair	1 (1)	

Data presented as n (%). VSD, Ventricular septal defect; TOF, tetralogy of Fallot; RVOTO, right ventricular outlet tract obstruction.

TABLE E2. Clinical characteristics summarized by early (<7 days of diagnosis) versus late (≥7 days after diagnosis) plication versus no plication

Characteristic	No plication (n = 128)	Early plication (n = 16)	Late plication (n = 14)	Overall P value (early vs late)
Age, d, median (IQR)	138 (11-682)	8 (5-18)	17 (6-62)	<.001 (.33)
Male sex, n (%)	79 (62)	9 (56)	11 (79)	.39 (.26)
Ventricular physiology, n (%)				.33 (.44)
Univentricular	31 (24)	4 (25)	6 (43)	
Biventricular	97 (76)	12 (75)	8 (57)	
Risk adjustment for congenital heart surgery, n (%)				.38 (.34)
1	4 (3)	0 (0)	0 (0)	
2	37 (29)	1 (6)	4 (29)	
3	48 (38)	5 (31)	6 (43)	
4	24 (19)	7 (44)	3 (21)	
5	7 (5)	2 (13)	1 (7)	
Missing	8 (6)	1 (6)	0 (0)	
Median sternotomy in index operation, n (%)	121 (95)	14 (88)	14 (100)	.38 (.49)
Previous surgery, n (%)	37 (29)	1 (6)	5 (36)	.10 (.07)
CPB time, min, mean ± SD	137 ± 63	137 ± 45	162 ± 54	.41 (.23)
Cross-clamp time, min, median (IQR)	127 (99-157)	122 (104-174)	133 (126-195)	.25 (.26)
Use of deep hypothermic circulatory arrest, n (%)	23 (18)	11 (69)	3 (21)	<.001 (.01)
Mode of diagnosis, n (%)				.19 (1.00)
Ultrasound	128 (100)	15 (94)	14 (100)	
Direct	0 (0)	1 (6)	0 (0)	
Diaphragm activity on ultrasound, n (%)				.001 (.02)
Paresis	89 (70)	3 (19)	9 (64)	
Paralysis	37 (29)	13 (81)	5 (36)	
Missing	2 (2)	0 (0)	0 (0)	
Invasive ventilation at diagnosis, n (%)	125 (98)	16 (100)	13 (93)	.35 (.47)
Noninvasive ventilation following diagnosis, n (%)	47 (38)	8 (53)	9 (64)	.23 (.85)
Total duration of positive pressure ventilation, d, median (IQR)	7 (3-12)	10 (7-14)	30 (22-39)	<.001 (<.001)
ICU discharge from index surgery, d, median (IQR)	8 (5-16)	20 (13-23)	35 (27-61)	.048
ICU discharge from plication, d, median (IQR)		3 (3-10)	3 (2-9)	.59
Hospital discharge from index surgery, d, median (IQR)	16 (10-35)	30 (21-36)	57 (41-75)	.126
Hospital discharge from plication, d, median (IQR)		10 (7-21)	13 (9-27)	.78

IQR, Interquartile range; CPB, cardiopulmonary bypass; SD, standard deviation; ICU, intensive care unit.

TABLE E3. Odds ratios of undergoing diaphragm plication

Predictor variable	OR (95% CI)	P value
Age	0.996 (0.991-0.998)	.025
Age ≤1 y vs >1 y	11 (2.2-200)	.021
Single ventricle	1.6 (0.6-3.6)	.31
Median sternotomy	0.8 (0.2-5.6)	.80
CPB time	1.0 (0.996-1.01)	.39
DHCA	3.9 (1.7-9.2)	.002
Total ventilation days	1.0 (0.99-1.01)	.76

OR, Odds ratio; CI, confidence interval; CPB, cardiopulmonary bypass; DHCA, deep hypothermic circulatory arrest.