

Early diagnosis of diaphragm palsy after pediatric cardiac surgery and outcome after diaphragm plication – A single-center experience

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ABSTRACT

- Objective** : The aims of our prospective observational study were to evaluate the (1) reliability of clinical signs in the early detection of diaphragm palsy (DP); (2) reliability of ultrasonography using echo machine as a bedside tool for the diagnosis of DP; and (3) does early diaphragm plication result in the improved outcome? We also sought to determine the incidence and predominant risk factors for DP and diaphragm plication at our center.
- Materials and Methods** : This prospective observational study included patients with suspected DP from January 2015 to December 2018. Patients with suspected DP were initially evaluated by bedside ultrasonography using echo machine and confirmed by fluoroscopy. Diaphragm plication was considered for patients having respiratory distress, difficult weaning, or failed extubation attempt without any obvious cardiac or pulmonary etiology. Patients were followed for 3 months after discharge to assess diaphragm function.
- Results** : A total of 87 patients were suspected of DP based on clinical signs. DP was diagnosed in 61 patients on fluoroscopy. The median time from index operation to diagnosis was 10 (1–59) days. Diaphragm plication was done among 52 patients and not done in nine patients. Bedside ultrasonography using echo machine was 96.7% sensitive and 96.15% specific in diagnosing DP. Early plication (<14 days) significantly reduced the need for nasal continuous positive airway pressure (65% vs. 96%, $P = 0.02$), duration of mechanical ventilation (12 vs. 25 days, $P = 0.018$), intensive care unit (ICU) stay (25 days vs. 39 days, $P = 0.019$), and hospital stay (30 days vs. 46 days, $P = 0.036$).
- Conclusion** : Hoover’s sign and raised hemidiaphragm on chest X-ray are the most specific clinical signs to suspect unilateral DP. Bedside ultrasonography using an echo machine is a good diagnostic investigation comparable to fluoroscopy. Early plication facilitates weaning from the ventilator and thereby decreases the ICU stay and hospital stay.
- Keywords** : Diaphragm palsy, diaphragm plication, pediatric cardiac surgery

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INTRODUCTION

Diaphragm palsy (DP) due to reversible or irreversible phrenic nerve injury is one of the major complications following pediatric cardiac surgery.^[1-5] The older patients usually remain asymptomatic except for elevated ipsilateral hemidiaphragm, pulmonary atelectasis, and recurrent lung collapse on chest X-ray. However, in younger patients and patients with univentricular physiology, DP may lead to altered systemic and pulmonary blood flow pattern. Therefore, younger patients tend to become symptomatic with dyspnea, tachypnea, failed extubation or recurrent reintubation, prolonged ventilation, pneumonia, and sepsis.^[2,3]

Early diagnosis of DP is important for the improved outcome, and it requires early weaning, experience, and clinical suspicion. The diagnosis of DP is usually suspected based on clinical signs and confirmed by fluoroscopic evaluation of diaphragm movement in inspiration. However, fluoroscopic evaluation of the diaphragm requires transport of a critically ill patient to the cath lab and exposure to ionizing radiation. Therefore, diagnosis is usually delayed especially in neonates and sick patients. Recently, studies have shown that ultrasonographic assessment of diaphragm is reliable in adults with sensitivity and specificity comparable to fluoroscopy.^[6,7] However, data on the use of bedside ultrasonography using echo machine for diaphragm assessment after pediatric cardiac surgery is limited.

Some studies have found that recovery of diaphragmatic function requires variable period ranging from days to months, and some may not recover, suggesting unpredictable course.^[6,7] However, awaiting spontaneous recovery of diaphragmatic function requires prolonged mechanical ventilation. While studies have shown the advantages of early diaphragmatic plication in view of early extubation, decreasing intensive care unit (ICU) stay and hospital stay, decreasing morbidity and thereby improved outcome.^[8,9] However, the timing of plication varies from early to late in different studies.

Thus, there is still a gray zone both in the diagnosis and management of DP after pediatric cardiac surgery. The aims of our prospective observational study were to evaluate the (1) reliability of clinical signs in the early detection of DP; (2) reliability of ultrasonography using echo machine as a bedside tool for the diagnosis of DP; and (3) does early diaphragm plication result in improved outcome? We also sought to identify the incidence and risk factors for DP and diaphragm plication at our center.

MATERIALS AND METHODS

This prospective observational study was conducted from January 2015 to December 2018. The study was approved

by the institutional ethics committee and informed written consent was obtained from relatives of all the patients. Patients with an elevated hemidiaphragm on preoperative chest X-ray and patients on ventilator prior to surgery were excluded from the study. Preoperative, intraoperative, and postoperative data were collected prospectively. To assess the complexity of the patients, the RACHS-1 score was determined for all the patients.

Diagnosis of diaphragmatic palsy

We suspected DP in patients who had failed extubation or difficult weaning without obvious cardiac or pulmonary etiology; patients who developed any of the following signs with the commencement of weaning mode of ventilator: Hoover's sign (paradoxical thoracic movement), decreased breath sounds on the ipsilateral side, and recurrent or persistent lung collapse; Patients who had a persistent need for nasal continuous positive airway pressure (CPAP) or elevation of hemidiaphragm on chest X-ray after extubation. To verify the change in position of the diaphragm, we compared the chest X-ray performed on spontaneous breathing with preoperative chest X-ray.

All the patients with suspected DP were initially evaluated by bedside ultrasonography using an echo machine and then confirmed by fluoroscopy. On bedside ultrasonography using echo machine, paradoxical movement of the diaphragm was diagnosed as palsy, while absent or decreased movement was diagnosed as paresis.

Diaphragm plication surgery

We performed diaphragm plication in patients <6 months of age, difficult weaning or one or more failed attempts of extubation, or persistent need for nasal CPAP after the extubation. However, diaphragm plication was deferred in patients with no or minimal respiratory distress after extubation, decreasing requirement for CPAP, and no haziness or collapse of the lung on chest X-ray.

The diaphragmatic plication is performed through an ipsilateral lateral thoracotomy incision in the fifth or sixth intercostal space. Several 5-0 polypropylene sutures with Teflon pledgets were used to flatten the diaphragm with some tension. Early plication was defined as plication up to 14 days after index operation, while late plication was defined as plication after 14 days after index operation. In all the patients with DP with or without diaphragmatic plication, Diaphragmatic Proprioceptive Neuromuscular Facilitation^[4] was performed.

Follow-up

All the patients were followed up at 3 months after discharge with clinical examination, chest X-ray, and echocardiography.

Statistical analysis

All continuous variables are expressed as mean ± standard deviation or median with interquartile range. Categorical data are expressed as frequencies and proportions. Univariate linear regression was used to identify the direction and strength of associations between risk factors, diaphragm plication, and outcomes. For the statistical analysis, we used the version-16 (SPSS Inc, Chicago, U.S.A) with $P \leq 0.05$ considered significant.

RESULTS

During the study period, out of 8103 pediatric cardiac surgery based on clinical signs, 87 patients were suspected of DP. DP was diagnosed in 61 patients on fluoroscopy. The median age of the patients with DP was 105 days (1-1800 days) and predominantly occurred in males (87%). DP was most commonly right sided 31 (50.8%) and one patient (1.6%) had bilateral DP. Other clinical characteristics are shown in Table 1. Overall and in infants, ASO (Arterial switch operation) was the most common, while beyond infancy, TOF (Tetralogy of fallot) repair was the most commonly (6/11 patients, 55%) associated with DP. Among the closed heart surgery, modified BT (Blalock-taussig shunt) shunt was the most common cause of DP (7%). The distribution of DP per surgery is illustrated in Figure 1. Among the 61 patients, 52 underwent diaphragm plication, while 9 were managed conservatively [Figure 2].

Diagnosis of diaphragmatic palsy

The median delay in the diagnosis of DP from index surgery was 10 days (1-59 days). Twenty-four patients (39%) were diagnosed within 7 days, 15 patients (24.6%) between 7 and 14 days, and 22 patients (36.4%) were diagnosed after 14 days of the index operation. As shown in Figure 3, among the 87 patients suspected of DP, failed extubation was

the most common clinical sign (48 patients, 55.2%) followed by Hoover’s Sign (44 patients, 50.1%) and difficult to wean from the ventilator (42 patients, 48.3%).

Bedside ultrasonography using echo machine detected abnormal diaphragm motion in 60 patients and was negative for DP in 27 patients. Fluoroscopy confirmed DP in 61 patients, while 26 patients had normal diaphragm movement.

Assuming that fluoroscopic assessment is the gold standard in assessing hemidiaphragm motion, we compared the results of clinical signs and echocardiographic assessment with fluoroscopy. As shown in Table 4, none of the clinical sign was very sensitive (32.8%-65.6%); however, raised hemidiaphragm on chest X-ray (92.3%) and Hoover’s sign (84.6%) had the highest specificity

Table 1: Clinical characteristics of diaphragm palsy

Clinical characteristics	Total (n=61), n (%)
Age (days) (median)	105 (1-1800)
Male	53 (87)
Ventricular physiology	
Univentricular	10 (16)
Biventricular	51 (84)
RACHS score n (%)	
1	2
2	25
3	10
4	24
5	
Cardiopulmonary bypass	
Yes	54 (89)
Closed heart surgery	10 (16)
DHCA	4 (7)
Diaphragm activity	
Paralysis	48 (79)
Paresis	13 (21)
Laterality	
Right	31 (50.8)
Left	29 (47.8)
Bilateral	1 (1.6)
Previous surgery	5 (8)
Requirement of nasal CPAP	48 (79)
Reintubation before plication	52
Mortality	2 (3)

DHCA: Deep hypothermic circulatory arrest, RACHS: Risk adjustment for congenital heart surgery, CPAP: Continuous positive airway pressure

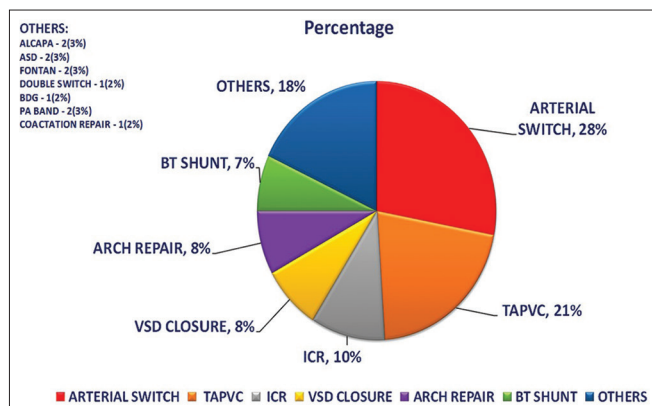


Figure 1: Incidence of diaphragm palsy among various surgeries

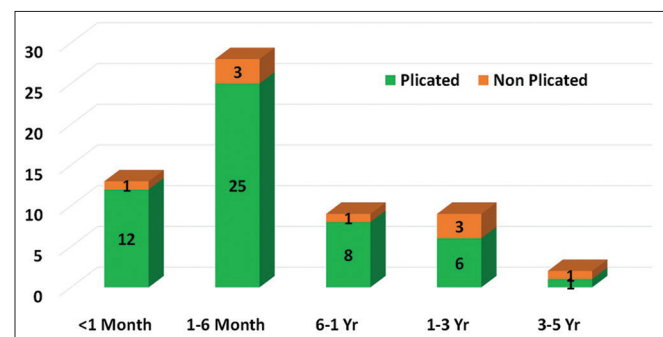


Figure 2: Age-wise distribution of diaphragm palsy and diaphragm plication

Table 2: Outcome after plicated and nonplicated patients

Clinical characteristics	Plication group (n=52), n (%)	Without plication group (n=9), n (%)	P
Age (days) (median)	97 (1-1800)	270 (15-1590)	0.03
Male (n)	45 (74)	8 (89)	0.73
Ventricular physiology			
Univentricular (n)	10 (19)	0	0.342
Biventricular (n)	42 (81)	9 (100)	
RACHS score n (%)			
1	2 (4)	0 (0)	0.678
2	20 (38)	5 (56)	0.419
3	10 (19)	0 (0)	0.322
4	20 (38)	4 (44)	0.906
5			
Cardiopulmonary bypass			
Yes (n)	45 (87)	9 (100)	0.546
No (n)	7 (13)	0	0.546
Closed heart surgery (n)	10 (19)	0	0.4
Cardiopulmonary bypass time (min)	110.54±88.64	91 (51-150)	0.576
DHCA (n)	4 (8)	0	0.89
Diaphragm activity			
Paralysis (n)	45 (87)	3 (33)	0.002
Paresis (n)	7 (13)	6 (67)	
Laterality			
Right	31 (51)	5 (82)	0.88
Left	29 (48)	4 (18)	0.78
Bilateral	1 (1.6)	0	
Previous surgery	5 (10)	0	0.75
Diagnosis from index surgery (days)	1 (2-59)	7 (0-16)	0.078
Requirement of nasal CPAP	39 (75)	7 (78)	0.71
Recurrent lung collapse (n)	18 (27)	9 (67)	0.049
Extubation after hours	116 (4-720)	96 (5-144)	0.05
Total days of mechanical ventilation	22.5 (1-203)	3 (1-11)	0.032
Sepsis	40 (77)	5 (55)	0.34
ICU stay from index operation, days	33 (7-242)	17 (6-23)	0.048
Hospital stay from index op days	41.5 (12-260)	26 (12-32)	0.042
Mortality	2 (4)	0	

DHCA: Deep hypothermic circulatory arrest, RACHS: Risk adjustment for congenital heart surgery, CPAP: Continuous positive airway pressure, ICU: Intensive care unit

Table 3: Outcome of early plication and late plication patients

Characteristics	Early plication (n=29), n (%)	Late plication (n=23), n (%)	P
Age (days) (median)	150 (14-1080)	90 (1-1800)	0.614
Male sex (n)	18 (62)	19 (83)	0.25
Ventricular physiology			
Univentricular (n)	9 (31)	1 (4)	0.038
Biventricular (n)	20 (69)	22 (96)	
Cardiopulmonary bypass			
No	6 (21)	1 (4)	0.191
Yes	23 (79)	22 (96)	
Cardiopulmonary bypass duration (min)	81±67	148±99	0.005
DHCA (n)	2 (7)	2 (9)	0.777
Hoover's sign	23 (79)	11 (48)	0.037
Diaphragm activity			
Paralysis (n)	26 (90)	19 (83)	0.741
Paresis (n)	3 (10)	4 (17)	0.741
Total duration of mechanical ventilation (median) (days)	12 (1-75)	25 (5-203)	0.019
Sepsis (n)	20 (69)	21 (91)	0.105
Requirement of nasal CPAP (n)	19 (65)	22 (96)	0.021
ICU stay from index surgery (days)	25 (7-100)	39 (20-242)	0.019
ICU stay after plication (days)	15 (2-88)	11 (4-143)	0.459
Hospital stay from index surgery (days)	30 (12-122)	46 (31-260)	0.036
Hospital stay after plication (days)	24 (7-110)	20 (9-219)	0.445

DHCA: Deep hypothermic circulatory arrest, CPAP: Continuous positive airway pressure, ICU: Intensive care unit

and positive predictive values (PPVs) (92.9% and 90.9%, respectively). Ultrasonography using echo machine was false negative in two patients and false positive in

one patient. The sensitivity and specificity of bedside ultrasonography using echo machine were 96.7% and 96.15%, respectively.

Table 4: Sensitivity and specificity of signs

	Sensitivity (%)	Specificity (%)	Positive predictive value (%)	Negative predictive value (%)
Positive Hoover’s sign	65.6	84.6	90.9	51.2
Raised hemidiaphragm on chest X-ray	42.6	92.3	92.9	40.7
Difficult weaning from ventilator	39.3	30.8	70.1	57.1
Failed extubation	37.7	3.85	47.9	2.6
Recurrent lung collapse	32.8	42.3	57.1	21.15
Bedside ultrasonography using echo machine	96.7	96.15	98.3	92.6

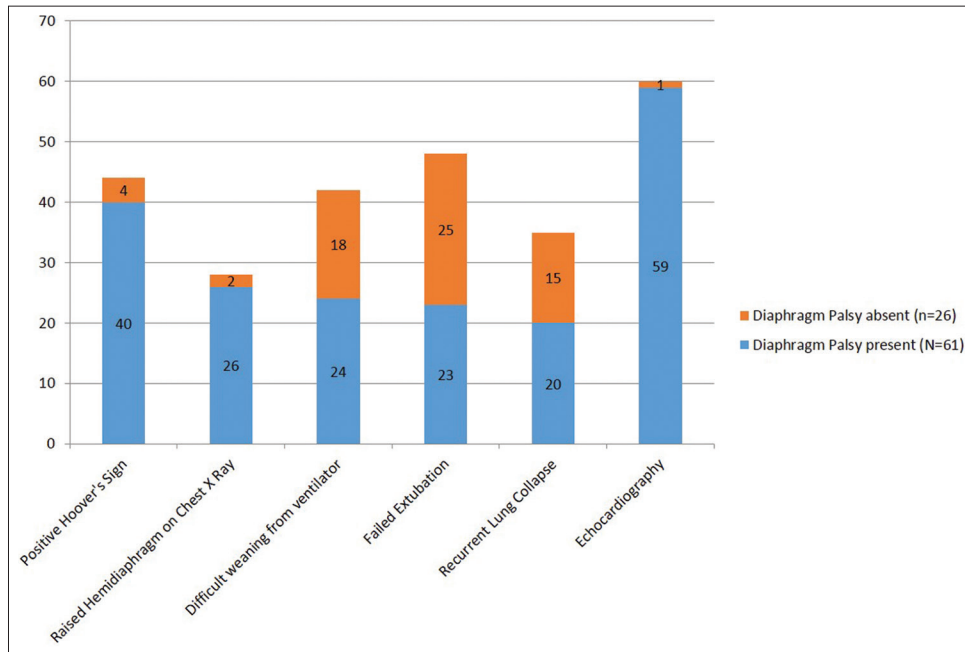


Figure 3: Signs and diagnosis of diaphragm palsy

Diaphragm plication: Comparison of patients with or without diaphragm plication

We found that the incidence of diaphragmatic plication was 0.65% at our institute. The median delay between the diagnosis of DP and diaphragm plication was 2 days (1-13 days). Forty-seven (90.1%) patients underwent plication within 24 h of diagnosis, while plication was delayed in 5 patients due to associated complications (4-13 days). Post plication, 28 (53.9%) patients were extubated within 48 h, 10 patients (19.2%) were extubated within 96 h, and nine patients were extubated after 96 h. The rest of five patients required prolonged ventilation despite diaphragm plication due to other complications (residual cardiac defect, pneumonia, acute renal failure, neurological complications, sepsis, and bilateral DP) underwent tracheostomy. Twenty-two patients (42%) had at least one failed extubation after diaphragm plication. Twenty of these 22 patients were subsequently extubated, while two patients required tracheostomy due to prolonged ventilation. Nine patients (14.8%) were managed conservatively, six patients had paresis, and three patients had palsy.

There were five infants including one neonate and four patients were older than 1 year.

In comparison to nonplication group, patients in plication group were significantly younger (97 days vs. 270 days, $P = 0.03$), had a higher incidence of diaphragm paralysis (87% vs. 33%, $P = 0.001$), required prolonged mechanical ventilation (22.5 vs. 3 days, $P = 0.031$), prolonged duration of ICU stay (33 vs. 17 days, $P = 0.048$), and hospital stay (41.5 vs. 26 days, $P = 0.042$). There were two deaths in the plication group due to sepsis.

There were no significant differences between the groups regarding RACHES score, duration of cardiopulmonary bypass, use of DHCA, need for CPAP, and laterality. Although not statistically significant, all the patients with re-operative surgery and univentricular repair were in the plication group [Table 2].

Comparison of early plication and late plication

Of 52 patients, 29 patients underwent early plication (≤ 14 days), while 23 patients underwent late plication (> 14 days). Compared with the late plication group, patients in the early plication group were

older (150 days vs. 90 days), although the difference was not statistically significant ($P = 0.614$). The incidence of positive Hoover' sign was significantly higher in the early plication group (79% vs. 48%, $P = 0.038$). Patients requiring nasal CPAP after extubation were significantly less in the early plication group (65% vs. 96%, $P = 0.02$). Duration of mechanical ventilation (12 vs. 25 days, $P = 0.018$), ICU stay (25 days vs. 39 days, $P = 0.019$), and hospital stay (30 days vs. 46 days, $P = 0.036$) were significantly less in the early plication group. However, there was no statistically significant difference in duration of ICU ($P = 0.45$) and hospital stay ($P = 0.44$) after diaphragm plication [Table 3].

During follow-up, the affected diaphragm was still raised compared to preoperative chest X-ray in 20 patients (40%) in the plicated group and in five patients (55.5%) in the nonplicated group, while the normal position of the diaphragm maintained in 30 patients (60%) in the plicated patients and four patients (44.4%) in the nonplicated group.

DISCUSSION

The incidence of DP in literature varies from 0.33% to 5.7% in retrospective studies^[3,8,9-11] and 0.5%–12.8% in prospective studies.^[12-15] The difference in reported increased incidence in prospective studies may be due to asymptomatic course, uneventful recovery of DP, or difficulties in diagnosis. In our prospective study, the incidence of DP after pediatric cardiac surgery was 0.75%.

Role of clinical signs in the diagnosis of diaphragm palsy

Our results show that positive Hoover's sign has high specificity (84.6%) for the diagnosis of DP. In patients with unilateral diaphragmatic paralysis, Hoover's sign can diagnose the side of DP by the outward movement of the lower intercostal muscles on the affected side while indrawing of lower intercostal muscles on the normal side. In case of bilateral diaphragmatic palsy, respiration is paradoxical. Further, in patients with diaphragm paresis, a respiratory pattern may be normal during calm breathing, while the exertion (crying, pain, activity, and associated other respiratory problems) may unmask the paradoxical thoracic movement. However, the sensitivity of Hoover's sign was low (65.6%) in our study. This probably due to limited exposure of respiratory pattern due to the presence of dressing, intercostal drain, or other associated problems like stridor. Our results show that elevated hemidiaphragm on chest X-ray is also quite specific (92.3%) but has low sensitivity (42.6%) for the diagnosis of DP.

We found that the other three signs, i.e., recurrent lung collapse, difficult weaning from the ventilator,

or multiple failed extubation, had both low sensitivity and specificity. This is probably because other cardiac and respiratory etiologies are more common reasons contributing to the above-mentioned signs. Still, we believe that all these clinical signs should be diligently sought after pediatric cardiac surgery as they may be the only clinical signs to raise the clinical suspicion of DP.

In our study, the incidence of ipsilateral recurrent lung collapse was more in nonplicated group compared to the plication group (67% vs. 27%, $P = 0.049$). This is because the diaphragm on the affected side cannot resist negative intrapleural pressure and moves paradoxically during inspiration. This reduces the functional residual capacity and facilitates alveolar collapse and atelectasis. Recumbent position in the infants further leads to a reduction in vital capacity and their small intrabronchial caliber facilitates obstruction and atelectasis by retained secretions.^[2,4,16] This is further substantiated by the increased requirement of nasal CPAP in nonplicated patients.

Drawback of all these signs is that they manifest only when we start weaning the patient from the ventilator. Therefore, the diagnosis of DP is usually delayed especially in neonates and infants, as the patient may be on prolonged positive pressure ventilation due to causes such as unstable hemodynamic, sepsis, pneumonia, acute kidney injury, fluid overload, and inability to maintain pO₂ and pCO₂. In our study, the median duration between index cardiac surgery and the diagnosis of DP was 10 days (1–59 days). This considerable time period was, in most cases, due to the clinical condition of patients necessitating positive pressure ventilation.

Role of ultrasonography using echo machine

Our results show that bedside ultrasonography using an echo machine is an appropriate and accurate bedside method for assessing diaphragm function after pediatric cardiac surgery. Ultrasonography using echo machine correctly identified affected hemidiaphragms in 96.7% of patients resulting in a sensitivity of 96.7% and negative predictive value of 92.6%. While the sensitivity of ultrasonography using echo machine for identifying DP that was later on plicated was 100%. Specificity and PPV of echocardiography were 96.15% and 98.3%, respectively. Studies have also shown that both fluoroscopy and bedside ultrasonography using echo machine are equally useful with a sensitivity of 100% and specificity of 74% and 81%, respectively.^[15] We believe that further increase in experience in detection of diaphragm movement with ultrasonography using echo machine may obviate the need for fluoroscopy for the diagnosis of DP and may also shorten the delay in diagnosis.

Predictors of diaphragm plication

Age correlation

In our study, young age and DP were significant predictors for the diaphragm plication. Our results are consistent with other studies.^[5] In neonates and infants, the diaphragm is the only strongest muscle of inspiration as intercostal muscles are weak and the mediastinum is mobile. Therefore, raised hemidiaphragm leads to the impingement of mediastinal contents on the contralateral lung compromising the limited cardiorespiratory reserve.^[16] Beyond infancy, the diaphragm contributes to only 25% of the inspiratory function. Therefore, unilateral DP is usually well tolerated in older children due to better cardiorespiratory reserve and compensatory mechanisms.^[17] Despite the above-stated reasons, surgeons and critical care staff bias can not be ruled for the high incidence of diaphragm plication in infants and neonates.

Paresis versus plication

Compared to DP; in diaphragm paresis, the position of the diaphragm is relatively lower, and hence, it maintains better residual pulmonary function. The probability of spontaneous recovery is also higher in patients with paresis.

Univentricular repair and plication

In our series, 100% of patients with univentricular physiology who had DP required plication and 90% of patients underwent early plication. Part of this may have been our bias toward early plication in patients with univentricle physiology even if the patient was in compensated respiratory status. In patients with univentricular physiology, lack of inspiratory negative intrathoracic pressure and increased pulmonary vascular resistance leads to increased work of breathing and reduces the passive venous pulmonary bloodstream. These together results in increased systemic venous pressure and causes ascites and pleural effusion.^[1,3,18,19] Diaphragm plication in these patients improves the pulmonary hemodynamic and reduces the systemic venous pressure.^[20]

Surgery

Similar to other studies, we also found the highest incidence of DP after ASO (28%) which may be due to extensive dissection, especially branch PA dissection, harvesting of autologous pericardium, or complete resection of the thymus.^[2,13,15,16] In our study, the incidence of DP after re-operative cardiac surgery was 8% (three patients underwent staged univentricular repair and two patients underwent biventricular repair). Re-operative cardiac surgery was also associated with an increased risk of DP due to fibrosis and adhesions in the mediastinum, making it difficult to identify the phrenic nerve during surgery.^[5,16,21]

Studies have reported DHCA as a significant risk factor for DP.^[9] In our study, we did not find DHCA as a risk factor. This may be due to the infrequent use of DHCA pericardial ice slush for hypothermia in our institute.

Early versus late diaphragm plication

Earlier, a conservative approach for 4–6 weeks with the use of prolonged mechanical ventilation was standard.^[16,22] Nowadays, diaphragm plication is widely accepted and standard of treatment for patients with DP with compromised cardiorespiratory function. However, the timing of plication varies from early to late in different studies. In our study, we found that patients who underwent early diaphragm plication had significantly less morbidity in the form of reduced mechanical ventilation time, lesser need for nasal CPAP, and reduced ICU as well as hospital stay. Therefore, at our institute, we prefer to perform early plication in patients who require prolonged respiratory support unless the patient is extubated with comfortable breathing with no or minimal need for nasal CPAP. Our results are in concordance with other studies.^[3,9,14,23]

We observed that delay in diagnosis of DP due to positive pressure ventilation, expected diaphragm movement recovery, avoidance of further surgery, surgeon's hesitancy for plication, and associated comorbidities resulted in delayed plication. However, studies have revealed that late plication may jeopardize the results of successful surgical plication due to atrophy of the diaphragm.^[1]

Timing of plication

We believe that the diagnosis of DP itself should not be considered as an indication for diaphragm plication and decision for plication should be considered in the light of the age of the patient, clinical condition, diaphragm paralysis or paresis, need for invasive or noninvasive ventilation, and oxygen requirement. Further, before considering the diaphragm plication, other causes of respiratory distress, for example, pneumonia, lung collapse, and residual cardiac defect, should be identified and corrected adequately. Our results show that when plication is done early in indicated patients, it significantly improves morbidity (ICU stay and hospital stay). However, it does not significantly change the post plication ICU and hospital stay whether plication was done early or late. This is probably because of associated cardiorespiratory and other systemic comorbidities. In our institute, we defer the plication if a patient is extubated, breathing comfortably, and no or minimal need for CPAP. In our series, 14.7% of patients were successfully managed without plication.

Replication

The effectiveness of plication can be assessed by the position of the diaphragm on chest X-ray, decreased work of breathing, and decreased requirement of respiratory

support. In our study, one patient could not be weaned from the ventilator post plication and had persistent paradoxical thoracic movement and elevated dome of the diaphragm on a chest X-ray. Repeat fluoroscopy confirmed significant residual paradoxical diaphragm movement on the affected side. Patients underwent re-diaphragm plication and extubated after 24 h post re-plication.

Prevention of diaphragm palsy

We made changes in surgical strategies to prevent DP. Use of suction tip or forceps for blunt dissection and minimal handling near the phrenic nerve are the keys for the prevention of DP.

Studies have shown that the plicated diaphragm reveals the return of function that improves over time.^[16,24] However, mid-term and long-term follow-up studies are required to evaluate the outcome after diaphragm plication and movement of the diaphragm. In our study, at follow-up, 40.1% of patients had good diaphragm recovery, while other (13.6%) patients had partial recovery of diaphragm function. In the rest, 46.3% of patients, there was no recovery of diaphragm function. Our results are consistent with the literature.^[16,24]

CONCLUSION

Hoover's sign and raised hemidiaphragm on chest X-ray are valuable clinical signs to suspect unilateral DP with good specificity but low sensitivity. Ultrasonography using echo machine is a good bedside diagnostic investigation with sensitivity and specificity comparable to fluoroscopy. Age <6 months, univentricular heart physiology, and DP rather than paresis are the most important risk factors for diaphragm plication. Early plication facilitates weaning from the ventilator, decreases the need for noninvasive ventilation, and decreases ICU stay and hospital stay.

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Conflicts of interest

There are no conflicts of interest.

REFERENCES

1. Talwar S, Agarwala S, Mittal CM, Choudhary SK, Airan B. Diaphragmatic palsy after cardiac surgical procedures in patients with congenital heart. *Ann Pediatr Cardiol* 2010;3:50-7.

2. Ross Russell RI, Helms PJ, Elliott MJ. A prospective study of phrenic nerve damage after cardiac surgery in children. *Intensive Care Med* 2008;34:728-34.
3. Lemmer J, Stiller B, Heise G, Hübler M, Alexi-Meskishvili V, Weng Y, *et al.* Postoperative phrenic nerve palsy: Early clinical implications and management. *Intensive Care Med* 2006;32:1227-33.
4. Vidhyadhari BS, Madavi K. Influence of proprioceptive neuromuscular facilitation techniques on diaphragm muscle activity and pulmonary function in subjects with Guillain-Barre syndrome. *Indian J Physiother Occup Ther* 2015;9:24-8.
5. Tönz M, von Segesser LK, Mihaljevic T, Arbenz U, Stauffer UG, Turina MI. Clinical implications of phrenic nerve injury after pediatric cardiac surgery. *J Pediatr Surg* 1996;31:1265-7.
6. Iverson LI, Mittal A, Dugan DJ, Samson PC. Injuries to the phrenic nerve resulting in diaphragmatic paralysis with special reference to stretch trauma. *Am J Surg* 1976;132:263-9.
7. Watanabe T, Trusler GA, Williams WG, Edmonds JF, Coles JG, Hosokawa Y. Phrenic nerve paralysis after pediatric cardiac surgery. Retrospective study of 125 cases. *J Thorac Cardiovasc Surg* 1987;94:383-8.
8. Georgiev S, Konstantinov G, Latcheva A, Mitev P, Mitev I, Lazarov S. Phrenic nerve injury after paediatric heart surgery: Is aggressive plication of the diaphragm beneficial? *Eur J Cardiothorac Surg* 2013;44:808-12.
9. Floh AA, Zafurallah I, MacDonald C, Honjo O, Fan CS, Laussen PC. The advantage of early plication in children diagnosed with diaphragm paresis. *J Thorac Cardiovasc Surg* 2017;154:1715-21.
10. Lemmer J, Stiller B, Heise G, Alexi-Meskishvili V, Hübler M, Weng Y, *et al.* Mid-term follow-up in patients with diaphragmatic plication after surgery for congenital heart disease. *Intensive Care Med* 2007;33:1985-92.
11. Dagan O, Nimri R, Katz Y, Birk E, Vidne B. Bilateral diaphragm paralysis following cardiac surgery in children: 10-years' experience. *Intensive Care Med* 2006;32:1222-6.
12. de Leeuw M, Williams JM, Freedom RM, Williams WG, Shemie SD, McCrindle BW. Impact of diaphragmatic paralysis after cardiothoracic surgery in children. *J Thorac Cardiovasc Surg* 1999;118:510-7.
13. Zhao HX, D'Agostino RS, Pitlick PT, Shumway NE, Miller DC. Phrenic nerve injury complicating closed cardiovascular surgical procedures for congenital heart disease. *Ann Thorac Surg* 1985;39:445-9.
14. van Onna IE, Metz R, Jekel L, Woolley SR, van de Wal HJ. Post cardiac surgery phrenic nerve palsy: Value of plication and potential for recovery. *Eur J Cardiothorac Surg* 1998;14:179-84.
15. Langer JC, Filler RM, Coles J, Edmonds JF. Plication of the diaphragm for infants and young children with phrenic nerve palsy. *J Pediatr Surg* 1988;23:749-51.
16. Joho-Arreola AL, Bauersfeld U, Stauffer UG, Baenziger O, Bernet V. Incidence and treatment of diaphragmatic paralysis after cardiac surgery in children. *Eur J Cardiothorac Surg* 2005;27:53-7.

17. Robotham JL. A physiological approach to hemidiaphragm paralysis. *Crit Care Med* 1979;7:563-6.
18. Penny DJ, Redington AN. Doppler echocardiographic evaluation of pulmonary blood flow after the Fontan operation: The role of the lungs. *Br Heart J* 1991;66:372-4.
19. Redington AN, Penny D, Shinebourne EA. Pulmonary blood flow after total cavopulmonary shunt. *Br Heart J* 1991;65:213-7.
20. Ovroutski S, Alexi-Meskishvili V, Stiller B, Ewert P, Abdul-Khaliq H, Lemmer J, *et al.* Paralysis of the phrenic nerve as a risk factor for suboptimal Fontan hemodynamics. *Eur J Cardiothorac Surg* 2005;27:561-5.
21. Akbariasbagh P, Mirzaghayan MR, Akbariasbagh N, Shariat M, Ebrahim B. Risk factors for post-cardiac surgery diaphragmatic paralysis in children with congenital heart disease. *J Tehran Heart Cent* 2015;10:134-9.
22. Haller JA Jr., Pickard LR, Tepas JJ, Rogers MC, Robotham JL, Shorter N, *et al.* Management of diaphragmatic paralysis in infants with special emphasis on selection of patients for operative plication. *J Pediatr Surg* 1979;14:779-85.
23. Akay TH, Ozkan S, Gultekin B, Uguz E, Varan B, Sezgin A, *et al.* Diaphragmatic paralysis after cardiac surgery in children: Incidence, prognosis and surgical management. *Pediatr Surg Int* 2006;22:341-6.
24. Baker CJ, Boulom V, Reemtsen BL, Rollins RC, Starnes VA, Wells WJ. Hemidiaphragm plication after repair of congenital heart defects in children: Quantitative return of diaphragm function over time. *J Thorac Cardiovasc Surg* 2008;135:56-61.