IMPACT OF DIAPHRAGMATIC PARALYSIS AFTER CARDIOTHORACIC SURGERY IN CHILDREN

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Objectives: We sought to determine the prevalence and clinical impact of diaphragmatic paralysis caused by phrenic nerve injury after cardiothoracic surgery in children. **Methods:** A search of cardiology, radiology, and hospital databases identified 170 episodes of diaphragmatic paralysis after cardiothoracic surgery in 168 children operated on from 1985 to 1997. Medical records were reviewed to determine demographics, details of the operation and postoperative course, diagnostic features and management of diaphragmatic paralysis, and follow-up status. **Results:** The prevalence of diaphragmatic paralysis was 1.6% (95% confidence interval 1.4%-1.8%). Median age at operation was 6 months (range <1 day-14.4 years). Median time from the operation to the initial investigation was 5 days (range <1 day-61 days), with 57% of patients receiving mechanical ventilation at diagnosis. Diaphragmatic plication was performed in 40% of the patients at a median interval from the initial investigation of 15 days (range 3 days-11.1 months). Significant independent factors associated with increased postoperative hospital stay were lower patient weight at operation, previous cardiothoracic operations, bilateral diaphragmatic paralysis, increased interval from operation to investigation, mechanical ventilation at the time of investigation, and diaphragmatic plication. Confirmed recovery of diaphragmatic function was noted before hospital discharge in only 15 episodes. **Conclusions:** Diaphragmatic paralysis complicating cardiothoracic surgery continues to occur in the current era, with a significant impact on morbidity. Smaller patients with bilateral hemidiaphragmatic paralysis, requiring mechanical ventilation, may represent a higher risk subgroup to target for increased diagnostic suspicion and more aggressive management; early spontaneous recovery is rare. (*J Thorac Cardiovasc Surg* 1999;118:510-7)

Many surgical advances have improved survival related to congenital heart disease, and this had been accompanied by trends toward performing surgical palliation or repair at younger ages. However, for some complex lesions, outcomes continue to be less optimal. Diaphragmatic paralysis resulting from injury of the phrenic nerve during cardiothoracic surgery continues to occur.¹⁻¹⁸ This complication can cause serious

morbidity in infants and young children. In these young children, weakness of the intercostal muscles, increased compliance of the chest wall, horizontal orientation of the rib cage, recumbent position, and mobile mediastinum may contribute to increased respiratory distress.¹⁹ Many of these children may require diaphragmatic plication to facilitate successful weaning from mechanical ventilation.

We sought to determine the prevalence of diaphragmatic paralysis after cardiothoracic surgery in children, associated risk factors, criteria for diaphragmatic plication, clinical impact, and prognosis for spontaneous recovery of diaphragmatic function in a single institution's current experience.

Methods

Study population. Between January 1985 and December 1997, a total of 10,395 cardiovascular surgical procedures

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were performed at the Hospital for Sick Children. All patients with the diagnosis of postoperative diaphragmatic paralysis caused by phrenic nerve injury were identified in the Cardiology database of the Division of Cardiology and the Radiology database of the Division of Radiology, The Hospital for Sick Children, and were included in the present study. The diagnosis was verified in the medical records for all patients, and patients who were coded incorrectly and did not have phrenic nerve injury after cardiothoracic surgery were excluded.

Measurements. The cardiology and hospital records for all patients were reviewed. Data collected included demographics, anatomic diagnosis, details of the operation and postoperative course, diagnostic features and management of diaphragmatic paralysis, and follow-up data.

Data analysis. Data are described as frequencies, medians with ranges, and means with standard deviations. In cases in which data are missing, the number of non-missing values is given. In all statistical analyses, age and weight at operation, the intervals from the operation to the first confirmatory investigation and hospital discharge, and the interval from first confirmatory investigation to diaphragmatic plication were analyzed with a log transformation. Factors associated with diaphragmatic paralysis were sought with χ^2 tests and Kruskal-Wallis analysis of variance. Factors associated with status at initial diagnostic investigation and with diaphragmatic plication were tested with Fisher's exact tests, χ^2 tests, Kruskal-Wallis analysis of variance, *t* tests, and analysis of variance. Independent factors associated with time to final extubation in those patients who were receiving mechanical ventilation at the time of first investigation were explored in the Cox proportionate hazard regression modeling. Independent factors associated with length of postoperative hospital stay were explored in the Cox proportionate hazard regression modeling. SAS version 6.12 software (SAS Institute, Inc, Cary, NC) was used to perform all statistical analyses by means of default settings.

Results

Prevalence of diaphragmatic paralysis. From the cardiology and radiology databases, 170 episodes of diaphragmatic paralysis after cardiothoracic operations were identified and verified in 168 patients operated on between January 1985 and December 1997 at The Hospital for Sick Children, Toronto. Two patients had 2 different episodes of diaphragmatic paralysis. Over the study period, 10,395 cardiothoracic operations were performed, with a prevalence of diaphragmatic paralysis of 1.6% (95% confidence interval [CI] 1.4%-1.8%). Six surgeons performed the operations, with prevalences of 0.3%, 1.1%, 1.2%, 1.2%, 1.9%, and 2.2%. The operations were divided into mechanistic categories as follows, with many procedures falling into more than 1 category. Categories and the prevalence of diaphragmatic paralysis are as follows: systemic-pul-

monary arterial shunt placement or takedown, 3.0%; placement or takedown of a systemic venous-pulmonary artery connection, 3.9%; intracardiac surgery including closure of septal defects or repair of atrioventricular valves, 1.7%; repair, resection, banding, patching, or conduit placement in the right ventricular outflow or main pulmonary artery, 2.2%; arterioplasty of the branch pulmonary arteries, 3.3%; repair, resection, or patching in the left ventricular outflow or aortic arch, 1.7%; correction of pulmonary venous anomalies, 2.0%; and miscellaneous repairs such as cardiac transplantation and elimination of isolated patent ductus arteriosus, 0.9%. Diaphragmatic paralysis was more prevalent in those patients who had had prior cardiothoracic operations (2.8%) than in those who had not (1.3%; $P < .001$). The prevalence increased significantly with time, with a prevalence of 1.2% (95% CI 0.9%-1.5%) from 1985 to 1990, increasing to 1.8% (95% CI 1.5%-2.2%) from 1991 to 1997 ($P = .006$). Patients with, versus without, diaphragmatic paralysis were significantly younger at operation (median 5.6 months, range 1 day-14.4 years, versus median 13.3 months, range <1 day-21 years; $P < .001$) and had longer postoperative hospital stays (median 26 days, range 5 days-7.1 months, versus median 10 days, range <1 day-1.8 years; $P < .001$).

Study subject characteristics. The patients comprised 98 boys and 70 girls ($n = 168$). Two patients had more than 1 episode of diaphragmatic paralysis. One patient with pulmonary atresia had right-sided diaphragmatic paralysis after a right thoracotomy for placement of an arterial shunt and required diaphragmatic plication. Subsequently, during complete repair through a median sternotomy, a left-sided paralysis developed, which required a plication. The other patient with truncus arteriosus had right-sided diaphragmatic paralysis after median sternotomy for complete repair, with documented recovery of function. Subsequently, during conduit replacement, bilateral paralysis developed and necessitated plication.

The median age at operation at the time of the episode was 6 months (range <1 day-14.4 years) with a median weight of 6.0 kg (range 0.69-38 kg). The surgical approach was through a median sternotomy in 134 episodes (79%), thoracotomy in 35 (21%), and both approaches in 1 episode. Of note, 2 operations with right-sided thoracotomy were associated with left-sided diaphragmatic paralysis, and 1 operation with left-sided thoracotomy was associated with right-sided diaphragmatic paralysis. We were unable to attribute this to any intravenous line placement or other invasive procedure, and we speculate that the phrenic nerve

Fig 1. State at initial diagnosis, management, and outcomes of diaphragmatic paralysis. *Includes 1 patient who required reintubation and mechanical ventilation, who was subsequently extubated after diaphragmatic plication.

injury may have been due to traction on contralateral structures. Fibrous adhesions were reported to be present in 67 episodes (39%), and previous cardiothoracic surgical procedures had been performed in patients having 83 episodes (49%), with 36 episodes (21%) related to more than 1 prior cardiothoracic operation.

Diagnosis of diaphragmatic paralysis. The reasons for suspicion of phrenic nerve injury and diaphragmatic paralysis ($n = 167$) included failure to wean from mechanical ventilation in 85 episodes (51%), the presence of an elevated hemidiaphragm on chest x-ray film in 85 (51%), signs of respiratory distress in 18 (11%), an asymmetric breathing pattern in 9 (5%), paradoxical movement of the epigastrium in 7 (4%), tachypnea in 5 (3%), recurrent pneumonia in 2 (1%), and recurrent unilateral lung collapse in 1 episode (<1%). In 2 episodes diaphragmatic paralysis was suspected because the phrenic nerve had been manipulated during the cardiothoracic operation. The method by which the diagnosis of diaphragmatic paralysis was made ($n = 167$) was clinical signs and chest radiography only in 15 episodes (9%), with confirmation by ultrasound imaging only in 135 (81%), fluoroscopy only in 5 (3%), and both ultrasound and fluoroscopy in 12 episodes (7%). The date of diagnosis was taken as the date of the first confirmatory test (ultrasound or fluoroscopy) or, in a minority of episodes, the date the diagnosis was first recorded in the medical record for those patients who did not have a confirmatory test. The median time from the operation to the first diagnostic investigation was 5 days (range <1 day–61 days).

Characteristics of diaphragmatic paralysis. Diaphragmatic paralysis occurred on the left side in 82

episodes (48%), right side in 78 (46%), and bilaterally in 10 episodes (6%). In those episodes with ultrasound or fluoroscopic imaging ($n = 154$), the motion of the affected hemidiaphragm was absent in 78 (51%) and paradoxical in 76 episodes (49%).

Status at the time of initial investigation. Status at the time of initial diagnostic investigation ($n = 159$) was mechanical ventilation in the intensive care unit in 91 episodes (57%), extubated but receiving supplemental oxygen in the intensive care unit in 32 (20%), receiving supplemental oxygen in the ward in 24 (15%), and breathing room air in the ward in 12 episodes (8%) (Fig 1). Patients supported by mechanical ventilation versus those breathing spontaneously were significantly younger at operation (median age 3.4 months, range <1 day–11.4 years, versus 8.0 months, range 2 days–14.4 years; $P = .03$), with lower weights (median 4.1 kg, range 1.3–38.0 kg, vs 7.4 kg, range 2.0–37.1 kg; $P = .002$).

Diaphragmatic plication. At our institution patients with an initial diagnosis of diaphragmatic paralysis may undergo a variable period of medical observation and respiratory management at the physicians' discretion before being considered for plication; criteria to define failure of this expectant strategy were not standardized. A total of 68 patients (40%) were managed with diaphragmatic plication, which was performed at a median interval of 21 days (range 6 days–11.2 months, $n = 66$) after the operation and at a median interval of 15 days (range 3 days–11.1 months, $n = 65$) after the initial diagnosis of diaphragmatic paralysis. One patient underwent diaphragmatic plication during the initial operation when it was believed that the

Table I. Factors associated with diaphragmatic plication

Variable	No plication (n = 102)	Plication (n = 68)	P value
Median (range) date of operation	9/1993 (7/1986–12/1997)	9/1990 (12/1984–5/1997)	<.001
Median age at operation	8.0 mo (2 d–14.4 y)	2.3 mo (<1 d–7.0 y)	.002
Median weight at operation	7.13 kg (0.69–38.0 kg)	4.08 kg (1.9–17.8 kg)	.001
Number of previous operations			
None	49	38 (44%)*	
One	32	15 (32%)	
More than one	16	15 (42%)	>.2
Presence of adhesions			
Absent	59	44 (43%)	
Present	43	27 (36%)	>.2
Median interval from operation to initial diagnostic test	5 d (n = 100, 1–61 d)	5 d (n = 67, <1–36 days)	>.2
Status at initial diagnostic test			
Mechanical ventilation in ICU	34	57 (63%)	
Supplemental oxygen only in ICU	27	5 (16%)	
Supplemental oxygen on ward	22	2 (8%)	
Room air on ward	11	1 (8%)	.001
Side of diaphragmatic paralysis			
Left hemidiaphragm only	51	31 (38%)	
Right hemidiaphragm only	45	33 (42%)	
Both	6	4 (40%)	>.2
Motion of affected hemidiaphragm			
Absent	56	30 (35%)	
Paradoxical	40	37 (48%)	.09

ICU, Intensive care unit.

*All percentages in parentheses represent the proportion of patients with that particular characteristic who underwent a diaphragmatic plication.

phrenic nerve had been transected, with confirmation of diaphragmatic paralysis 7 days after the operation. At the time of plication, 50 (77%) of 65 of these patients were receiving mechanical ventilation, with a median time to extubation of 4 days (range <1 day–65 days) after plication. Recorded reasons for plication included failure to wean or prolonged duration of mechanical ventilation in 56 patients (7 of whom were eventually extubated before plication was performed), presence of respiratory distress in 10, markedly elevated hemidiaphragm on chest x-ray film in 3, low transcutaneous oxygen saturations in 2, presence of chronic reactive airway disease in 1, persistent pleural effusions in 1, and known transection of the phrenic nerve at the initial operation in 1 patient.

Factors associated with diaphragmatic plication.

Since no standard protocol was in place to guide management after the diagnosis of diaphragmatic paralysis, characteristics were compared between patients who underwent plication versus those who had ongoing medical management (Table I) to determine patient selection biases regarding decisions to plicate. Patients who underwent diaphragmatic plication were operated on earlier in the experience, were significantly younger, weighed less, and were more likely to have been receiving mechanical ventilation in the intensive

care unit at the time of the initial diagnostic investigation. Plication was not significantly related to previous operations or adhesions, the underlying type of operation that was performed, the interval from the operation to the initial investigation, or the side or motion of the affected hemidiaphragm. In those patients who had diaphragmatic plication, the interval from diagnosis to plication was not significantly related to the age or weight at operation, a previous operation or adhesions, side or state of diaphragmatic paralysis, interval from the operation to diagnosis, or the length of the postoperative hospital stay. Patients who were receiving mechanical ventilation at the time of initial investigation had a significantly shorter time from diagnosis to plication (median 14 days, range 3–150 days) than those who had been successfully extubated before plication (median 27 days, range 15–337 days; $P = .002$).

Outcomes and impact of diaphragmatic paralysis.

There were 4 deaths before hospital discharge and an additional 17 late deaths at a median interval after the operation of 1.6 years (range 2.6 months–3.4 years). Patients who died were more likely to have had diaphragmatic plication (17/21, 81%) than those who were survivors (51/149, 34%; $P = .001$). The 4 deaths before hospital discharge all occurred in patients who had had plication, 3 with subsequent successful extu-

Table II. Independent factors associated with increasing length of postoperative hospital stay after cardiothoracic surgery in patients with diaphragmatic paralysis*

Variable	Parameter estimate (SE)	P value
Lower patient weight at operation (kg)†	0.6498 (0.2230)	.003
Previous cardiothoracic operations	-0.3438 (0.1498)	.02
Degree of diaphragm involvement		
Unilateral	Reference category	
Bilateral	-1.1562 (0.3759)	.002
Longer interval from operation to initial confirmatory investigation (days)†	-0.6387 (0.1171)	<.001
Mechanical ventilation in ICU at initial investigation for diaphragmatic paralysis	-1.7009 (0.2353)	<.001
Diaphragmatic plication‡	-0.6686 (0.2230)	.003

SE, Standard error; ICU, intensive care unit.

*From Cox's proportionate hazard modeling; nonsignificant factors include age at operation, adhesions, and state of the affected hemidiaphragm.

†Entered after logarithmic transformation.

‡Entered as a time-dependent explanatory variable.

bation from mechanical ventilation, and the cause of death was related to the underlying cardiac condition. None of the late deaths was related to the diaphragmatic paralysis. For hospital survivors, the median time spent in the intensive care unit ($n = 163$) was 11 days (range, <1 day–103 days) and the median length of hospital stay ($n = 165$) was 25 days (range 5–214 days).

The association of diaphragmatic plication with time to final extubation was explored in those patients who were receiving mechanical ventilation at the time of initial investigation ($n = 91$) or who had been extubated before diagnosis but had not thrived and required mechanical ventilation up to the time of their plication ($n = 1$) (excluding those patients who had remained extubated before their plication). The median time from diagnosis to final extubation in those patients who did not have plication was 7 days ($n = 43$, range 1–89 days) versus 19 days ($n = 47$, range 4–86 days) in those who required plication before they could finally be extubated. Of the patients who were receiving mechanical ventilation up to the time of their plication, the median time to final extubation after plication was 4 days (range 1–65 days). The interval from plication to final extubation was not significantly related to the interval from initial diagnosis to plication. Independent factors associated with time to final extubation were explored in the Cox proportionate hazard modeling for those patients receiving ventilatory support at the time

of initial diagnosis or up to their plication. Significant independent factors associated with a longer time to extubation after initial diagnosis included diaphragmatic plication (entered as a time-dependent explanatory variable; $P < .001$), bilateral hemidiaphragmatic paralysis ($P = .004$), and a longer interval from the operation to the initial diagnosis ($P = .03$).

Independent factors associated with length of postoperative hospital stay were sought in the Cox proportionate hazard modeling (Table II). Significant independent factors associated with increased length of postoperative stay were lower weight at operation, previous operations, bilateral diaphragmatic paralysis, mechanical ventilation in the intensive care unit at the time of investigation, increased interval from the operation to the initial investigation, and diaphragmatic plication (entered as a time-dependent explanatory variable). After controlling for these factors, age and date of operation, adhesions, and state of the affected hemidiaphragm were not significantly independently related to length of hospital stay. An additional analysis was performed in only those patients who had plication. The length of postoperative hospital stay for these patients was not significantly related to the interval from initial diagnosis to plication ($P = .89$), after controlling for weight at operation, previous operations, bilateral diaphragmatic paralysis, mechanical ventilation in the intensive care unit at the time of investigation, and interval from the operation to the initial investigation.

Recovery of diaphragmatic function. On follow-up assessments of hospital survivors, including clinical assessment, chest radiographs, ultrasound, fluoroscopy, or cardiac catheterization ($n = 147$), recovery of diaphragmatic function or a normal level of the diaphragm was noted in the medical record in 37 episodes (25%); in 110 episodes we noted persistent absence of diaphragmatic movement, paradoxical movement, elevation, or eventration of the hemidiaphragm. Only 15 occurrences of recovery, however, were confirmed with ultrasound or fluoroscopy, including 4 after diaphragmatic plication (confirmed 21, 36, 56, and 392 days after plication). In the 11 episodes that were not managed with plication, recovery was confirmed at a median interval of 14 days (range 6 days–5.2 years) after the cardiothoracic operation and occurred before extubation from mechanical ventilation in 4 episodes, before discharge from the hospital in 4, and after discharge from the hospital in 3 episodes. Kaplan-Meier estimates of confirmed recovery before hospital discharge or death without plication were 0.7% (95% CI 0%–2.0%) at 7 days after the operation,

4.8% (CI 1.0%-8.6%) at 14 days, and 7.5% (CI 1.1%-14%) at 1 month after the operation. In the Cox proportionate hazard modeling, no factor was significantly associated with confirmed recovery before hospital discharge, including age and weight at operation, previous operations or adhesions, the side and state of the paralyzed hemidiaphragm, and diaphragmatic plication (entered as a time-dependent explanatory variable).

Discussion

Prevalence of diaphragmatic paralysis. In our current study, diaphragmatic paralysis occurred in 1.6% of children after cardiothoracic surgery, similar to a previously published series from our institution with a prevalence of 1.6% for procedures performed from 1974 to 1985.⁹ The reported prevalence in other retrospective studies varies from 0.3% reported by Stone and associates¹⁰ to 5.7% reported by Smith and colleagues,⁸ although in the latter study only lateral thoracotomies were considered. Kunovsky and coworkers¹⁶ found a prevalence of 4.6% in their study, which included all palliative and corrective cardiothoracic operations.

A prevalence of 1.9% to 12.8%^{14,16,20} has been noted in prospective studies. The higher prevalence noted in prospective versus retrospective studies may have several explanations, including increased surveillance in prospective studies to detect asymptomatic cases by routinely performing percutaneous phrenic nerve stimulation to confirm the diagnosis of abnormal phrenic nerve latency.^{14,15,20} Many children with abnormal phrenic nerve latency do not have clinical symptoms, which are often the criteria prompting investigation and detection in retrospective series and some prospective series. In clinical situations, diaphragmatic paralysis is often first considered when clinical signs or respiratory difficulties are present. Asymptomatic cases often are first suspected when an elevated hemidiaphragm is noted on a follow-up chest x-ray film. Although both retrospective and prospective studies provide important information concerning the clinical presentation and impact of this complication, prospective studies with routine screening give the best estimates of prevalence and risk factors.

Relation to type of surgical procedure. The surgical procedure that is most often associated with an increased risk of phrenic nerve injury is the creation or takedown of a systemic-pulmonary artery shunt (most commonly a modified Blalock-Taussig shunt)^{2,6,8,9,13,16,18} Tonz and colleagues¹⁸ reported that up to 19% of patients with diaphragmatic paralysis had had a previous modified Blalock-Taussig shunt. In our series, surgical procedures

involving creation or takedown of both arterial and venous shunts, as well as surgical procedures on the branch pulmonary arteries, were associated with the highest prevalence of diaphragmatic paralysis.

Other factors associated with phrenic nerve injury. Risk factors for phrenic nerve injury have been suboptimally defined, but several factors have been variously reported to increase the prevalence. Previous cardiothoracic operations have been reported to increase the risk.^{2,6,9,10,13,14,18} In our series, previous cardiothoracic surgical procedures had been performed in 49% of episodes, similar to the findings of Watanabe and colleagues⁹ in an earlier series from our institution. We also noted a relative risk of 2.2 for patients with previous procedures. The higher risk related to repeat operations is most likely related to technical difficulties in dissection caused by fibrous adhesions surrounding the phrenic nerve, increasing the difficulty of identifying the different structures and thus making the nerve more vulnerable to unintentional injury.^{2,9,10,13,14,21} In our study, the presence of fibrous adhesions was reported in 39% of episodes. Unnecessary or careless dissection in the proximity of the phrenic nerve should be avoided.^{2,6,9,13,18,21} The use of electrocautery in the direct vicinity of the phrenic nerve has also been reported as a risk factor.^{2,6,9,10,13,16,21}

Effect of patient age and weight on clinical impact.

Phrenic nerve injury is less well tolerated in infants and small children than in older children.^{2,8-10,13,14,21,22} Several factors contribute to make younger children more vulnerable to respiratory complication related to loss of diaphragmatic function, including relative weakness of the intercostal muscles, greater compliance of the chest wall, the horizontal orientation of the rib cage, and increased mobility of the mediastinum.¹⁹ Infants prefer or are placed in a recumbent position, and this reduces the vital capacity and, due to the small caliber of the infant bronchial tree, facilitates retention of secretions and bronchial obstructive debris. Paradoxical movements of the diaphragm contribute to a decrease in pulmonary compliance. However, our institutional prejudice that children with paradoxical movement versus absence of motion of the affected hemidiaphragm have a more complicated clinical course was not confirmed by our data.

Diagnosis of phrenic nerve injury. Diaphragmatic paralysis should be suspected when there are unexplained difficulties in weaning the patient from mechanical ventilation, when there is unexplained respiratory distress or dependence on oxygen supplementation, or when the patient has a persistently elevated hemidiaphragm on the chest x-ray film. In our study, the diag-

nosis was confirmed with only ultrasound imaging in 135 episodes, only fluoroscopy in 5, and both ultrasound and fluoroscopy in 12 episodes. Many authors have primarily used or advocate fluoroscopy as the investigation of choice.^{2-6,8,10,22} In a previous retrospective study of 125 patients with diaphragmatic paralysis from our institution, Watanabe and coworkers⁹ reported that fluoroscopy was the only method used to confirm the diagnosis in 101 patients, ultrasound only in 14, and both fluoroscopy and ultrasound in 10 patients. More recently, other authors^{12,16,17} have primarily used or advocated ultrasound as the primary diagnostic method because ultrasound is associated with diagnostic capabilities similar to those of fluoroscopy, facilitates early diagnosis at the bedside, involves no patient discomfort, and is easy to repeat. The shift in confirmatory testing from fluoroscopy to ultrasound at our institution reflects the increasing preference for ultrasound, given that the diagnosis can be confirmed in the intensive care unit, without transfer of a potentially unstable patient to the fluoroscopy suite.

Management of diaphragmatic paralysis. The management of diaphragmatic paralysis remains controversial. Some authors^{3,5,6,9,15-17,22} report that optimal management involves an anticipatory approach with long-term ventilatory support. Haller and colleagues³ concluded in their study that a trial of continuous positive airway pressure breathing is the best form of management. This approach can also function as a critical differential test to identify the infants who will benefit from diaphragmatic plication, with the optimal period of observation being 4 to 6 weeks. We did not assess the use of this therapy in our study. Although most authors^{2,4-6,8-11,13,17,21,22} agree on the role of diaphragmatic plication, there is controversy regarding the optimal timing of the plication. Bingham¹ reported the first use of diaphragmatic plication as treatment for diaphragmatic paralysis in 1954 and stated that plication should be undertaken if an infant should appear to be in a life-threatening situation. Affatato,²¹ Shoemaker,⁴ and their associates reported that plication should take place as soon as the diagnosis of diaphragmatic paralysis is confirmed. Most authors,^{3,7,8,16,22} however, argue that it would be best to withhold diaphragmatic plication for 2 to 3 weeks in anticipation of potential spontaneous recovery of phrenic nerve function. Our study suggests that the potential for confirmed recovery of diaphragmatic function in this time period is very low and the decision to plicate should be based on the respiratory status of the patient.

After plication, Shoemaker and coworkers⁴ demon-

strated a reduction in the duration of ventilatory support, with extubation possible within 6 days of plication. In our study, 19 patients underwent diaphragmatic plication within 7 days of the initial diagnostic investigation, with a median time to extubation of 4.5 days after plication (vs 4 days if plication was performed after 7 days). Other reports provide evidence that aggressive diagnosis and treatment reduce morbidity, mortality, and duration of hospital stay.^{4,10} Plication does not preclude recovery of diaphragmatic function,^{2,9,10,16,21} although van Onna and coworkers²³ report delayed recovery in patients who had plication. Our data suggest that plication was not significantly associated with confirmed recovery of diaphragmatic function before hospital discharge.

In our study, the patients who were managed with a plication had surgery earlier in the experience, were significantly younger, weighed less, and were more likely to have been receiving mechanical ventilation in the intensive care unit at the time of initial diagnosis. Previous studies^{2-6,9,13,14,18,21} have suggested an age-dependent management strategy for patients with diaphragmatic paralysis, with plication particularly recommended for younger patients. Nonetheless, no randomized trials of management strategies related to diaphragmatic paralysis and the optimal duration and type of expectant management have been reported, and the optimal patient selection criteria for plication are unknown. Our data suggest that patients who underwent diaphragmatic plication had longer postoperative hospital stays (after controlling for available confounding characteristics) unrelated to the duration of expectant management from initial diagnosis to plication. This might suggest that plication is associated with increased morbidity, but since this was not a randomized trial, we cannot be certain that we have accounted for important confounding characteristics.

Significant independent factors associated with increased length of postoperative hospital stay included lower weight at operation, previous operations, bilateral diaphragmatic paralysis, mechanical ventilation in the intensive care unit at the time of the investigation, increased interval from the operation to the initial investigation, and diaphragmatic plication. After controlling for these factors, age of the patient, date of the operation, adhesions, and state of the affected hemidiaphragm were not significantly independently related to length of postoperative hospital stay. Although our results must be viewed in light of the limitations of a nonrandomized retrospective analysis, they may suggest that patients who are smaller, receiving mechanical ventilation, or who have bilateral paral-

ysis may benefit from a more aggressive approach, which may include earlier diaphragmatic plication.

Conclusions

Diaphragmatic paralysis caused by phrenic nerve injury during surgical palliation or repair of congenital heart disease continues to occur in the current era, with important effects on morbidity. Randomized clinical trials are needed to determine the role and optimal timing of diaphragmatic plication. Smaller patients with bilateral hemidiaphragmatic paralysis, who require mechanical ventilation, may represent a higher risk subgroup to target for increased diagnostic suspicion and more aggressive management; early spontaneous recovery is rare.

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