have been the mechanism of injury in this case, where no predisposing factor such as trauma or a bleeding disorder was present.

In conclusion, subdural hematoma and other neurologic abnormalities[10] should be suspected in the atypical case of post-lumbar-puncture cephalgia, especially in an obstetric patient.

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Anesthesiology
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Continuous Positive Airway Pressure in Hemidiaphragmatic Paralysis

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We have observed that infants and children with unilateral phrenic-nerve injury in respiratory distress are often able to maintain adequate ventilation while breathing spontaneously with continuous positive airway pressure (CPAP). The most common causes of phrenic injuries in children are brachial plexus injuries incurred at birth[1] and iatrogenic injuries incurred with retraction of the pericardium during cardiac surgical procedures.[2,3] Unilateral diaphragmatic paralysis in adults impairs ventilatory function but usually does not lead to significant embarrassment.[4] In infants and children, severe respiratory compromise can result. The opportunity to study a 6-month-old child with chronic respiratory distress due to unilateral diaphragmatic paralysis has allowed us to examine the pathophysiology of this problem and the therapeutic role of CPAP.

REPORT OF A CASE

The patient was a 6-month-old male infant, product of a complicated midforceps delivery, after which low Apgar scores had necessitated intubation of the trachea and mechanical ventilation. Physical examination showed right facial paralysis and hemiplegia. Initial roentgenograms showed symmetrically small lung volumes. Later, persistent elevation of the right hemidiaphragm was found. Although neurologic examination demonstrated gradual improvement, the patient was unable to be completely weaned from mechanical ventilation. He was transferred at the age of 6 months to Johns Hopkins Hospital. At that time, without ventilatory assistance, he rapidly became hypoxic and hypercapnic (arterial blood P_{O_2} 32 torr and P_{CO_2} 50 torr with $F_{I_{O_2}}$ .21). His breathing was labored, with predominantly left-sided chest movement and retractions in the left seventh and eighth intercostal spaces. Movement was diminished and breath sounds were decreased over the right hemithorax. Abdominal muscle tone, assessed by palpation, increased with expiration and decreased with inspiration. Paradoxical abdominal respiratory motion was not observed.

With transcutaneous phrenic-nerve stimulation, the diaphragmatic electromyogram was normal on the left but absent on the right. Cinefluoroscopy showed increased excursions of the left

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ABBREVIATIONS

P_{aw}	= airway pressure
P_{gas}	= gastric pressure
P_{es}	= esophageal pressure
P_{di}	= transdiaphragmatic pressure ($P_{gas} - P_{es}$)
ΔP_{di}	= difference between peak inspiratory and expiratory P_{di}s
P_{tp}	= transpulmonary pressure ($P_{aw} - P_{es}$)
C_{dyn}	= dynamic compliance of the lung
R_L	= pulmonary resistance
CPAP	= continuous positive airway pressure
IPPB	= intermittent positive-pressure breathing

TABLE 1. Results of Diaphragmatic Function Studies

	P_{gas}	P_{es}	ΔP_{es}	P_{di}	ΔP_{di}	P_{aw}	ΔP_{aw}
Transdiaphragmatic pressure during tidal breath							
CPAP 0.3 cm H_2O							
Peak expiratory pressure (cm H_2O)	15.5	14.2		1.3	18.7	0.3	
Peak inspiratory pressure (cm H_2O)	9.0	−11.2		20.0		0.3	
CPAP 9.3 cm H_2O							
Peak expiratory pressure (cm H_2O)	17.1	16.7		0.4	12.9	9.3	
Peak inspiratory pressure (cm H_2O)	9.3	−4.0		13.3		9.3	
Inspiratory effort with airway occluded							
CPAP 0.3 cm H_2O							
Peak inspiratory pressure (cm H_2O)			−21.6				−21.9
Maximum inspiratory effort during airway occlusion							
CPAP 0.3 cm H_2O							
Peak expiratory pressure (cm H_2O)	10.4	−0.5		10.9	37.6		
Peak inspiratory pressure (cm H_2O)	10.1	−38.4		48.5			

TABLE 2. Results of Pulmonary Function Studies during Quiet Tidal Breathing

	P_{tp} End-expiratory	P_{tp} End-inspiratory	ΔP_{tp}	Tidal Volume (ml)	Respiratory Rate (Breaths/Min)	$\dot{V}_E$ (ml/min)	C_{dyn} (ml/cm H_2O)	Pulmonary Resistance (cm H_2O/ml/sec)
CPAP 0.3 cm H_2O	−4.1	4.6	8.7	44.2	40	1768	5.08	0.07
CPAP 9.3 cm H_2O (preoperative)	−2.0	8.1	10.1	51.8	39	2020	5.23	0.06
CPAP 0 (postoperative, 1 month)				50.0				

hemidiaphragm, which was three to four ribs lower than the right hemidiaphragm. The right hemidiaphragm moved paradoxically relative to the spine. With continuous positive airway pressure (CPAP) of 10 cm H_2O during spontaneous respiration, the right hemidiaphragm was one rib space lower, and showed only minimal paradoxical motion. Arterial blood-gas values with $F_{I_{O_2}}$ .30 were P_{O_2} 77 torr and P_{CO_2} 37 torr. Pulmonary and diaphragmatic function studies were performed with and without CPAP (see tables 1 and 2). A diagnosis of permanent nerve injury was made and the right hemidiaphragm was surgically plicated.

MATERIALS AND METHODS

Studies performed prior to operation were done while the infant had a 4.0-mm endotracheal tube in place. He was seated in the upright position and had one 3-cm latex balloon positioned in the distal esophagus and another in the stomach. The volume of air in the balloons was adjusted so that all studies were performed on the flat portion of the balloons' pressure volume curves. The pressure in each balloon was recorded and transdiaphragmatic pressure (P_{di}) calculated.[5] Airway pressure was obtained just proximal to the endotracheal tube. A pneumotachograph between the endotracheal tube and CPAP line measured flow, which was electronically integrated for tidal volume. The level of CPAP was controlled by placing the expiratory line under water. Line flow exceeded peak inspiratory flow. P_{di} was measured at CPAP 0 and 10 cm H_2O during ten spontaneous respirations. Measurements were also made while the infant made inspiratory efforts against an occluded airway. Mean values for pulmonary compliance and inspiratory resistance during ten spontaneous respirations with CPAP 0 and 10 H_2O are reported.[6] ETT resistance was measured and subtracted from the total resistance measured to give pulmonary resistance (R_L). A month after surgical plication of the paralyzed hemidiaphragm, a resting tidal volume was measured with a face mask and pneumotachograph.

RESULTS

The results of the studies of diaphragmatic function prior to operation are shown in table 1. The change in transdiaphragmatic pressure (ΔP_{di}) during tidal breathing decreased by a third with the application of CPAP. During inspiratory efforts, with an occluded airway, the inspiratory changes in airway and esophageal pressures were similar. The maximum ΔP_{di} measured during airway occlusion during two consecutive obstructed inspiratory efforts was 37.6 cm H_2O.

The results of pulmonary function studies performed during quiet tidal breathing, with and without

CPAP, are presented in table 2. Reflecting a larger lung volume, transpulmonary pressures (P_{tp}) were increased by CPAP. The larger change in transpulmonary pressure (ΔP_{tp}) reflected the increase of tidal volume by CPAP, while the increased minute ventilation (V_E) was consistent with the decrease in arterial blood P_{CO_2}. A resting tidal volume a month postoperatively was similar to the preoperative tidal volume during CPAP (table 2).

Discussion

This infant's respiratory distress was due to a paralyzed hemidiaphragm. The efficacy of CPAP in improving his respiratory status was demonstrated by: 1) clinical observations of decreased respiratory distress; 2) improvement in arterial blood gases; 3) increased tidal volume and minute ventilation. Unlike other patients who have been treated with CPAP, this child had a normal cardiovascular system. However, even with the variable of cardiac disease eliminated, interpretation of this study is complicated because of 1) increased expiratory abdominal pressures, and 2) the questionable validity of esophageal pressure as a reflection of pleural pressure.

The increased expiratory abdominal pressure, which is normally less than the inspiratory pressure, correlates with the clinical observation of increased expiratory abdominal muscle tone. During a forced expiration, the diaphragm can be passively distended by an increased abdominal pressure to a point where a pressure gradient is established across it, creating a large positive expiratory P_{di} ($P_{gas} - P_{es}$). Thus, the ΔP_{di} (inspiratory P_{di} − expiratory P_{di}) could appear diminished. However, in our patient, the expiratory P_{di} of only 1.3 cm H_2O suggests that there was neither active diaphragmatic tension nor significant passive distention.

The ability of esophageal pressure to reflect mean pleural pressure accurately during tidal breathing is a critical problem. In the abdomen, the fluid contents evenly distribute changes in abdominal pressure. However, in the thorax, local pleural pressure differences are created during tidal breathing by chest-wall distortion, *e.g.*, paradoxical hemidiaphragmatic movement. This problem is eliminated when the airway is occluded since there is no change in lung volume and hence, the change in pressure is the same everywhere in the respiratory system. This was documented by the equal changes in esophageal and airway pressures during obstructed inspiratory efforts (table 1). Thus the ΔP_{di} measured during complete airway obstruction was a valid and useful measure of diaphragmatic function. We used the esophageal pressure as a measure of pleural pressure during tidal breathing, even though we were reluctant to accept it without reservation.

The integrated functional integrity of the inspiratory muscles was determined by the change in esophageal (or airway) pressure during the maximum inspiratory effort against a totally occluded airway (−0.5 cm H_2O to −38.4 cm H_2O). The ΔP_{di} of 37.6 cm H_2O preoperatively documented the integrity of the functional hemidiaphragm to support ventilation.[5]

The lack of dramatic changes in dynamic compliance and pulmonary resistance with CPAP suggests that they were not significantly affected by the maneuver. It is possible that an increase in compliance in the lung ipsilateral to the paralyzed hemidiaphragm due to increased recruitment of airways could have been offset by a decrease in compliance of the other lung at its larger volume. The small decrease in resistance would be expected as lung volume increased.[7]

The physiologic basis for the significant increase in tidal volume with CPAP may lie in the marked increase in efficiency for ventilation for a given ΔP_{di}. Hagan *et al.*[8] demonstrated that CPAP reduced chest wall distortion in neonates during inspiration. Our physical examination and fluoroscopic findings suggest that CPAP stabilized both the rib cage and the paralyzed hemidiaphragm. The immediate result was a larger tidal volume and apparently more efficient use of the force generated by the functioning hemidiaphragm. With active abdominal expiration, the transpulmonary pressure at end expiration without CPAP was −4.1 cm H_2O, a pressure at which widespread airway closure would exist. CPAP, though not eliminating expiratory airway closure, decreased it (P_{tp} −2.0), possibly allowing the inspiratory P_{di} generated to maintain ventilation more efficiently. Since the paralyzed hemidiaphragm is functionally analogous to a flail chest, ventilation of a more compliant lung would result in less paradoxical motion. An alternative explanation for the decreased paradoxical hemidiaphragmatic motion is that the lung, held at a higher volume by CPAP, is considerably less deformable.[9] The lung itself would therefore oppose any movement of the paralyzed hemidiaphragm into the thorax.

Changes in abdominal pressure may be critical in respiration with a paralyzed hemidiaphragm, for three reasons. The increased expiratory abdominal pressure should push the functioning hemidiaphragm up into the thorax, giving it a better mechanical advantage and longer length for an optimal inspiration. Second, the increased expiratory abdominal pressure should fix the paralyzed hemidiaphragm high in the chest, decreasing paradoxical motion during inspiration, thus increasing the efficiency of the functional hemidiaphragm. Finally, while an increase in the expiratory intercostal muscle tone will tend to decrease rib cage volume, by virtue of the linkage between the abdomen and rib cage postulated by Goldman and Mead,[10] it may be that the increased expiratory abdominal pressure could tend to maintain rib-cage volume.

We conclude that in patients who can generate an adequate ΔP_{di} during an obstructed inspiratory effort, a trial of CPAP may permit time for functional recovery without the need of either IPPB ventilation or surgical diaphragmatic plication. Since there is no published information available to answer the question of whether surgical plication in the infant or child with a temporary hemidiaphragmatic paralysis may have long-term adverse effects on the normal growth and development of the lung, it appears prudent to refrain from surgical intervention until permanent injury is confirmed. With convincing evidence of phrenic-nerve injury causing permanent hemidiaphragmatic paralysis, surgical plication is indicated when it has also been demonstrated that the infant can do well with CPAP alone, *i.e.*, the functional hemidiaphragm will allow adequate ventilation when the paralyzed hemidiaphragm is stabilized.

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Anesthesiology
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Serum Potassium Levels Following Transfusion of Frozen Erythrocytes

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The role of frozen, deglycerolized erythrocytes is assuming greater importance in the management of patients receiving massive transfusions.[1,2] Advantages cited by the proponents of frozen erythrocytes over blood with added citrate–phosphate–dextrose (CPD) are: longer shelf life,[3] prevention of alloimunization,[4] decreased risk of transfusion hepatitis,[5] and improved viability of function of erythrocytes.[6] Hyperkalemia, which might occur with transfusion of stored CPD blood[7] is noticeably absent with transfusion of frozen erythrocytes. Although it has been demonstrated that intracellular potassium levels in frozen, thawed, deglycerolized, and washed erythrocytes tend to decrease,[8] serum potassium values in patients receiving frozen erythrocytes have not previously been reported. This investigation was undertaken to study the effect of transfusion of frozen erythrocytes on serum potassium values in patients who receive such transfusions.

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Materials and Methods

Twenty-eight adult patients, 11 women and 17 men, whose ages ranged from 48 to 61 (mean 54) years,