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Early assessment of diaphragmatic dysfunction in children in the ITU: chest radiology and phrenic nerve stimulation

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ABSTRACT: Diaphragmatic dysfunction is a common postoperative complication of cardiac surgery in children, with important effects on respiratory morbidity. Its early diagnosis, followed by prompt surgical intervention, has been shown to reduce morbidity. However, the commonest method of diagnosis, based on hemidiaphragmatic elevation on the chest radiograph, may be less accurate than direct techniques for assessing phrenic nerve function.

We have compared electrophysiological and radiological diagnoses of diaphragmatic abnormality in 100 children (aged 3 days to 17.5 yrs) undergoing cardiac surgery, looking at respiratory morbidity as assessed by the duration of ventilation, the time spent on the cardiac intensive care unit (CICU), and the requirement for reintubation.

Despite showing good reproducibility, radiological diagnosis was neither sensitive nor specific in identifying patients with electrophysiological phrenic nerve damage. Analysis of the measures of outcome supported the electrophysiological technique. Patients with electrophysiological evidence of damage had a longer duration of ventilation, spent longer on the CICU, and had a greater incidence of reintubation than either radiologically abnormal or "normal" patients.

Chest X-rays are not a good method for diagnosing phrenic nerve damage in the early postoperative period in children. If early diagnosis is needed, then direct assessment of phrenic nerve function, such as the measurement of phrenic latency, may be a better technique.
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Although diaphragmatic dysfunction is not a common problem in childhood, some groups of children are at particular risk. One such group is children undergoing cardiac surgery.

In these children, phrenic nerve damage can increase the mortality of surgery [1–4], and respiratory morbidity [1–6]. It also prolongs postoperative ventilation time [6–8], increases the length of stay on the cardiac intensive care unit (CICU), and the likelihood of reintubation [3, 6, 8].

The early diagnosis of phrenic nerve damage (PND), especially in infants, may allow early diaphragmatic plication, which has been shown to improve outcome [3, 9, 10]. However, such early diagnosis has traditionally relied on clinical suspicion, supported by radiographic evidence of elevation of the injured hemidiaphragm, and confirmed by fluoroscopy [3, 10, 11].

Chest radiography alone is prone to many interpretation errors, due to factors such as positive pressure ventilation, pleural effusion, parenchymal lung disease, and the practical problems of obtaining a good, erect, unrotated inspiratory film from the intubated child [3, 5, 12–15]. In the early postoperative period, there are also practical problems in using fluoroscopy. In order to assess diaphragmatic movement, the child needs to be breathing spontaneously and, consequently, this technique is often used late for confirmation of the diagnosis. Furthermore, children need to be moved to the radiology department for such studies.

Direct measurement of phrenic nerve function offers advantages over existing methods of diagnosing diaphragm injury. It is an objective measure, with high repeatability in adults, and we have recently assessed its inter- and intra-observer variability in children [16]. It is also noninvasive and well-tolerated, and can be used as early as 24 h following surgery [17].

We therefore compared the ability of phrenic nerve stimulation and early chest X-rays to diagnose PND in children recovering from cardiac surgery.

Methods

Study population

One hundred patients were entered into the study. Eligible children included all those admitted for cardiothoracic surgery, excluding any with known neuromuscular disorders. Informed parental consent was sought from all eligible families, and our study group represented 100 consecutive admissions into the study. The median age of the group was 2.8 yrs (range 3 days to 17.5 yrs). All but one patient had a cardiac operation; the other patient had a right lobectomy. Thirty six of the children had had previous cardiac operations. The study had hospital Ethics Committee approval.

Phrenic nerve conduction time was measured 24 h preoperatively, and between 24 and 48 h postoperatively, using a technique that we have described previously [16, 17], and based on original work by Sarnoff *et al.* [18] and Newsom Davis [19]. Briefly, the phrenic nerve is stimulated in the neck, and the resultant diaphragm compound muscle action potential (CMAP) recorded with surface electrodes on the chest wall. Amplification of the signal and its display on a time-based oscilloscope permits measurement of the nerve's latency as the time between stimulus and CMAP [19]. Electrophysiological PND (PNDe) was defined as an increase of more than 2 ms in the latency, when compared with its preoperative value [17], as we have evidence that this size of increase is more than double the expected measurement error [16].

Chest X-rays were taken for each patient in the immediate preoperative period, and on days 1 and 3 postoperatively. This is consistent with standard clinical practice in our CICU. The X-rays were then presented in random order, and reviewed "blind" by an experienced radiologist (CD-M), who was not clinically associated with the patients. Each film was assessed using two methods:

1. A subjective assessment was given as to whether the hemidiaphragms were normal or raised.
2. The absolute height of the dome of each hemidiaphragm was measured relative to the vertebral bodies.

Technical details of the film's quality were noted, along with patient position, and any other features that might obscure diaphragmatic position, such as pleural effusion and basal consolidation.

In order to assess the ability of X-rays and phrenic nerve stimulation to predict outcome, we looked at three measures of respiratory morbidity:

1. The duration of postoperative ventilation.
2. The need for reintubation.
3. The length of stay on the CICU.

Outcomes were compared in three subgroups;

1. Those with postoperative radiological evidence of diaphragm dysfunction ("Radiologically abnormal").
2. Those with PNDe ("PNDe").
3. Those without evidence of either ("Normal").

As positive pressure ventilation may normalize diaphragmatic position in patients with diaphragmatic weakness, intubated and extubated patients are presented separately.

The intra- and inter-observer error variability in chest X-ray reporting was separately assessed in 32 X-rays from the same population. These included preoperative and postoperative films from 16 patients, 8 with normal electrophysiological phrenic nerve function, and 8 with PNDe. Two radiologists reviewed the films independently and in random order, and were presented with the same films again, in a different order, the following day.

Results

Out of the 100 patients, 297 X-rays were examined. In three, no second postoperative film was available. On day 1, 56 patients were intubated, 41 were extubated, and 3 X-rays were uninterpretable. On day 3, 32 patients remained intubated, with 63 extubated, and 5 X-rays uninterpretable.

PNDe was diagnosed in 16 patients. In 12 patients, phrenic latency was prolonged by between 2.5 and 7.8 ms, and in 4 patients, phrenic latency was absent postoperatively.

Patients with PNDe required a median of 168 h postoperative ventilation (95% confidence interval (CI) 100–334 h) compared to 24 h (95% CI 14–32 h) in the radiologically abnormal group, and 16 h (95% CI 12–21 h) in the normal group (table 1). PNDe patients also spent more days in the CICU, with a median of 8 days (95% CI 4–19 days), compared to 2 days in the other two groups (table 1). The differences between PNDe patients and both other groups was significant at the 1% level for duration of ventilation, and at the 5% level for days in the CICU. More PNDe patients required reintubation (35.2%) than in the radiologically abnormal group (12.0%) and the normal group (9.2%), although this did not reach statistical significance.

Inter- and intra-observer variability for chest X-ray reporting was good, with both observers concurring in 123 out of 128 cases (96%). This includes each hemidiaphragm in 32 separate X-rays viewed on two occasions.

Table 1. – Comparison of outcomes in patients with no abnormalities, abnormal X-rays and electrophysiological phrenic damage

	Pts n	Duration of ventilation†	CICU† days	Reintubated %
Normal*	65	16 (12–21)	2 (1–2)	9.2
Radiologically abnormal	25	24 (14–32)	2 (2–3)	12.0
PNDe	16	168 (100–334)	8 (4–19)	35.2

The numbers in the three categories exceed 100 because six patients with radiological abnormalities also had PNDe. *: patients with normal X-rays and normal phrenic latency; †: median, and 95% confidence interval in parenthesis. CICU: cardiac intensive care unit; PNDe: electrophysiological phrenic nerve damage.

The repeatability for observer 1 was 63 out of 64, and for observer 2 was 60 out of 64 (table 2).

For all patients, the radiological opinion was predictive of PNDe in 2 out of 18 patients (11.1%), with a sensitivity of 12.5%, and a specificity of 80.2% (tables 3a and b). Chi-squared analysis of this group shows no statistical difference between methods (χ^2=0.47). On day 3, the predictive value of radiological opinion rose to 4 out of 16 (25.0%), with a sensitivity of 25.0% and specificity of 84.8% (table 4a and b). Chi-squared analysis of this group again shows no statistical difference (χ^2=0.91). Only 3 out of 32 (9.4%) of intubated patients had X-rays that were considered abnormal, compared to 13 out of 63 (20.6%) in the extubated patients. Thus, the radiological diagnosis of abnormal diaphragmatic position was notably more common in extubated than in the intubated patients.

In order to evaluate the importance of sequential changes in the X-ray, we compared the relative heights of the two hemidiaphragms preoperatively and on day 3 postoperatively. The relative change in hemidiaphragmatic position was assessed in 90 patients, with good quality films on both occasions. In 56 patients (62%) the right hemidiaphragm moved less than 1 vertebral body relative to the left, and there was no agreement between the degree of movement and PNDe.

Table 2. – Observer variability, comparing the 32 X-rays (64 hemidiaphragms) assessed on two separate occasions by the two radiologists

		Observer 1		
		Both normal	Both abnormal	Different
Observer 2	Both normal	58	0	1
	Both abnormal	0	1	0
	Different	2	2	0

Table 3. – Electrophysiological and radiological diagnosis in patients on Day 1

a) **Day 1** **Intubated patients**		Electrophysiological diagnosis	
n = 56		Normal	PNDe
Radiological diagnosis	Normal	35	12
	Abnormal	7	2
b) **Day 1** **Extubated patients**		Electrophysiological diagnosis	
n = 41		Normal	PNDe
Radiological diagnosis	Normal	30	2
	Abnormal	9	0

PNDe: electrophysiological phrenic nerve damage.

Table 4. – Electrophysiological and radiological diagnosis in patients on Day 3

a) **Day 3** **Intubated patients**		Electrophysiological diagnosis	
n = 32		Normal	PNDe
Radiological diagnosis	Normal	20	9
	Abnormal	1	2
b) **Day 3** **Extubated patients**		Electrophysiological diagnosis	
n = 63		Normal	PNDe
Radiological diagnosis	Normal	47	3
	Abnormal	11	2

PNE: electrophysiological phrenic nerve damage.

Discussion

It is difficult to decide on an appropriate "gold standard" for assessing diaphragmatic dysfunction. Fluoroscopy can be used in spontaneously breathing patients, but is an impractical procedure for intensive care, and is of little value in the early postoperative period. Direct comparison of PNDe with radiologically abnormal patients showed separate but indistinguishable groups, and we therefore used simple outcome measures which should be influenced by diaphragmatic dysfunction. Using such measures, patients with PNDe are clearly a group at significant risk of a prolonged postoperative course.

Phrenic nerve latency was chosen, as it can be performed at the bedside in any non-paralysed patient, is not affected by positive pressure ventilation, does not require co-operation from the patient and, when performed with surface stimulation and recording, is non-invasive and well-tolerated in both adults [20], and children [17]. Furthermore, unlike fluoroscopy, the study of normal controls is ethically practical, and the technique has been extensively studied in adults [19–21], and children [22, 23]. We used a threshold value of 2 ms as the increase in latency above which we identified electrophysiological damage based on intra-patient variability [16, 17]. We have reported on the clinical effects of phrenic nerve damage in children undergoing cardiac surgery, and using this threshold, have demonstrated a significant increase in respiratory morbidity in children so identified [24]. The incidence of PND in this study, 16%, is higher than commonly reported in the paediatric population. We believe this to be as a result of the prospective nature of the study, and the diagnosis is supported by the increased morbidity in this group. Figures from our previous work suggest a similar incidence [17], as the technique identifies patients in whom there is no clinical suspicion of PND.

The present results also suggest that patients with radiological changes, but normal electrophysiology, do not have phrenic damage, as this group do not have a significantly different outcome to "normal" patients (table 1). In this study, X-rays were presented blind and in random order, so that an independent assessment could be made, but the radiological diagnosis will usually be based on a series of X-rays and their evolution rather

than a single view, and this may affect their interpretation. However, in a secondary analysis we also showed that sequential films, assessed for a change in relative hemidiaphragm position, did not improve the prediction of PNDe.

Although many reports on phrenic nerve damage have accepted the inaccuracies of X-ray diagnoses, most clinicians still place great emphasis on radiology. The present data clearly demonstrate the deficiencies of this approach. Other practical and more reliable methods, such as phrenic nerve stimulation, should be used if early identification of PND is considered clinically important.

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