Journal of Pediatric Surgery (2010) **45**, 355–359

ELSEVIER

Journal of Pediatric Surgery

www.elsevier.com/locate/jpedsurg

Thoracoscopic repair of congenital diaphragmatic hernia: intraoperative ventilation and recurrence

Merrill McHoney, Luca Giacomello, Shireen A. Nah, Paolo De Coppi, Edward M. Kiely, Joe I. Curry, David P. Drake, Simon Eaton, Agostino Pierro*

Department of Paediatric Surgery, Great Ormond Street Hospital and the UCL Institute of Child Health, London WC1N 1EH, UK

Received 21 October 2009; accepted 27 October 2009

Key words:
Congenital diaphragmatic hernia;
Pediatrics;
Carbon dioxide;
Metabolism;
Outcome;
Thoracoscopy

Abstract

Introduction: Thoracoscopic repair of congenital diaphragmatic hernia (CDH) has been described, but its efficacy and safety have not been validated. The aim was to compare our experience of thoracoscopy with laparotomy repair.

Methods: After ethics approval, we reviewed the notes of neonates with CDH operated in our institution between 2003 and 2008. Two historical groups were compared: infants who underwent laparotomy (2003-2008) or thoracoscopy (2007-2008). Data were compared by *t* test or Mann-Whitney tests.

Results: Thirty-five children had open repair of CDH, and 13 had thoracoscopic repair. Groups were homogeneous for age and weight. Five (38%) neonates who had thoracoscopy were converted to open for surgical difficulties (n = 4) and O_2 desaturation (n = 1). Patch repair was used in 12 (34%) open and 6 (46%) thoracoscopic repairs. End-tidal CO_2 was significantly elevated during thoracoscopy, but this was not reflected in arterial CO_2 or pH. There were 3 (8%) recurrences after open repair and 2 (25%) after thoracoscopy ($P = .19$).

Conclusion: Thoracoscopic repair of CDH is feasible. Arterial blood gases should be closely monitored. Despite higher $EtCO_2$, conversion to open was mainly because of difficult repair. A randomized trial is necessary to assess the effect of thoracoscopy on ventilation and recurrences.

In recent years, there has been an increased use of minimally invasive techniques in both pediatric and neonatal surgery [1] and specifically in the repair of congenital diaphragmatic hernia (CDH). Although they can be repaired via a conventional open abdominal approach, a minimally invasive approach via laparoscopy or thoracoscopy is also possible. Sometimes this may be disadvantageous. For example, CO_2 is absorbed during insufflation into the chest and creation of a capnothorax [2,3], which can lead to significant metabolic and physiologic changes. These include a degree of right-to-left shunting, decreased venous return and cardiac output, and systemic hypertension or hypotension depending on complex interactions [4,5]. The impaired respiratory capacity imposed by lung collapse has significant implications for oxygenation and CO_2 excretion [6] and increase in arterial-alveolar CO_2 gradient [7].

Presented at the 56th Annual Meeting of the British Association of Paediatric Surgeons, Graz, Austria, June 18-20, 2009.

* Corresponding author. Department of Surgery, UCL Institute of Child Health, WC1N 1EH London, UK. Tel.: +44 0 20 7905 2175; fax: +44 0 20 7404 6181.

E-mail address: pierro.sec@ich.ucl.ac.uk (A. Pierro).

0022-3468/$ – see front matter © 2010 Elsevier Inc. All rights reserved.
doi:10.1016/j.jpedsurg.2009.10.072

Coupled with impaired ventilation, this can lead to a marked increase in end-tidal CO_2 ($EtCO_2$) in children undergoing thoracoscopy, which is generally higher than that seen during laparoscopy and in smaller children undergoing single lung ventilation [8].

In addition, little information is available on the recurrence rate after thoracoscopic repair of CDH. Therefore, the aims of this study were as follows: (i) to describe our initial experience of thoracoscopic CDH repair with specific reference to the effects of CO_2 insufflation on intraoperative hypercapnia and acid-base balance, (ii) to compare and contrast these changes between the open and the thoracoscopic repair, and (iii) to document the medium term recurrence rate after open and thoracoscopic repairs.

1. Methods

After obtaining approval from our institutional ethical committee, we performed a retrospective review of all patients with a diagnosis of CDH treated in our institution from January 2003 to December 2008. Patients who did not have antenatal diagnosis of CDH or respiratory distress at birth (late diagnosis) and those with diagnosis of Morgagni hernia were excluded.

Operative management in this time period involved 2 separate strategies. A laparotomy was used for repair of CDH until 2007. After gaining minimally invasive surgical experience, the option of thoracoscopy in those deemed suitable for this type of surgery was obtained. Therefore, from 2007, patients were managed either via laparotomy or thoracoscopy. There were 48 neonatal CDH repairs overall. From 2007, this included 20 infants of which 13 of whom had an initially thoracoscopic approach.

All patients were clinically stable at the time of repair. This was defined as cardiovascular stability (including patients who were on inotropes), with at least 12 hours elapsed since weaning from high-frequency oscillatory ventilation or extracorporeal membrane oxygenation (ECMO) to conventional ventilation, and an fractional inspired O_2 of 40% or less. No patient received inhaled nitric oxide at the time of surgery.

The 2 operations performed were as follows:

(i) *Open CDH repair* via an upper transverse abdominal incision [9]. To close the defect, we used interrupted nonabsorbable sutures (eg, Prolene and Ethibond) or a Dacron patch if necessary.

(ii) *Thoracoscopic CDH repair* [10]. Briefly, a 3- or 5-mm Hasson cannula was inserted through the third or fourth intercostal space in the posterior axillary line. The chest was insufflated to 5 to 8 mm Hg using CO_2 at a flow rate of 1 to 4 L/min. Surgery was performed with the aid of 2 working ports. The hernia contents were reduced in the abdomen, and if a hernia sac was present, this was not resected. The defect was closed with interrupted nonabsorbable stitches. If necessary, a Dacron patch was used to close the defect. To achieve closure of the defect in the posterior thoracic wall, the posterolateral stitches were ligated extracorporeally using 3 to 4 small skin incisions.

Data collected included age, weight, duration of operation, need for inotropes, and ECMO. Intraoperative arterial blood gas analysis was performed by the anesthetist as deemed necessary for clinical monitoring. A blood gas was performed at the beginning and end of surgery in all patients and at intervals during anesthesia as clinically indicated on an individual basis. The lowest recorded pH and peak $PaCO_2$ were defined as the lowest and highest recorded values throughout the operation respectively. End-tidal CO_2 (kPa) was measured on a continuous basis using a positive sampling system (Hewlett Packard, Boeblingen, Germany) and recorded every 15 minutes by the anesthetist. The highest end-tidal CO_2 recorded during the operation was defined as the peak.

Data were reported as mean ± SEM, unless otherwise stated. Demographic data are presented as median and range. Nonparametric data were compared using Mann-Whitney tests. Changes within each group over time were analyzed using repeated-measures analysis of variance. Differences between groups at time-points were compared by *t* test. *P* values of less than .05 were considered significant.

2. Results

There were 35 children who had open repair of CDH and 13 who had thoracoscopic repair. The 2 groups were comparable with regard to age and weight (Table 1), as well as the presence of major cardiac defects, need for preoperative ECMO, and the need for inotropes at the time of operation. Patients in both groups treated with ECMO were stabilized before operation, resulting in surgery in a few patients after 1 month of age.

Table 1 Demographic data between open and thoracoscopic groups (median and range, unless otherwise indicated)

	Open (n = 35)	Thoracoscopy (n = 13)	*P*
Age at operation (d)	11.7 (1-75)	12.5 (2-45)	.94
Weight at operation (kg)	3.6 (2-6)	4.2 (3-8)	.05
Major cardiac defects	8 (23%)	2 (15%)	.71
Preoperative ECMO	6 (17%)	2 (15%)	.88
Inotropic use at operation	3 (9%.)	2 (15%)	.60
Mean (SEM) duration of operation (h)	2.0 ± 0.1	3.3 ± 0.4	<.01

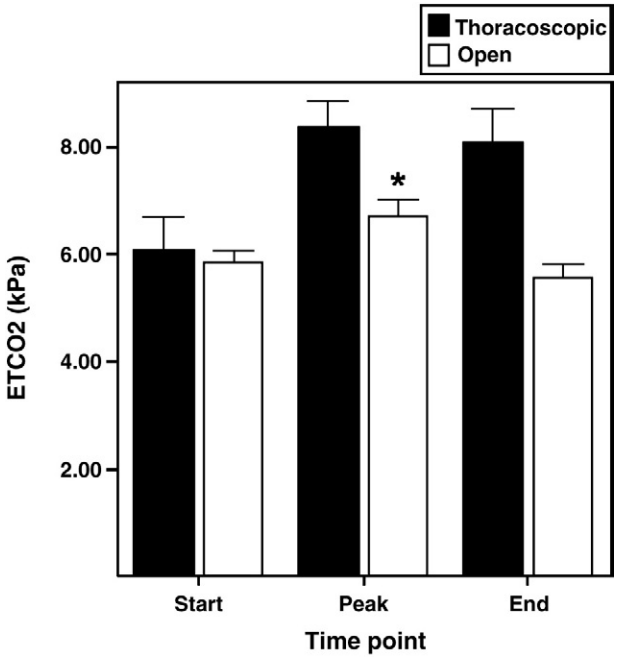

Fig. 1 End-tidal CO_2 levels during thoracoscopic and open repair of CDH. Bars represent mean, and error bars represent SEM. Peak levels were defined as the highest value recorded intraoperatively. *$P < .01$ between thoracoscopic and open groups.

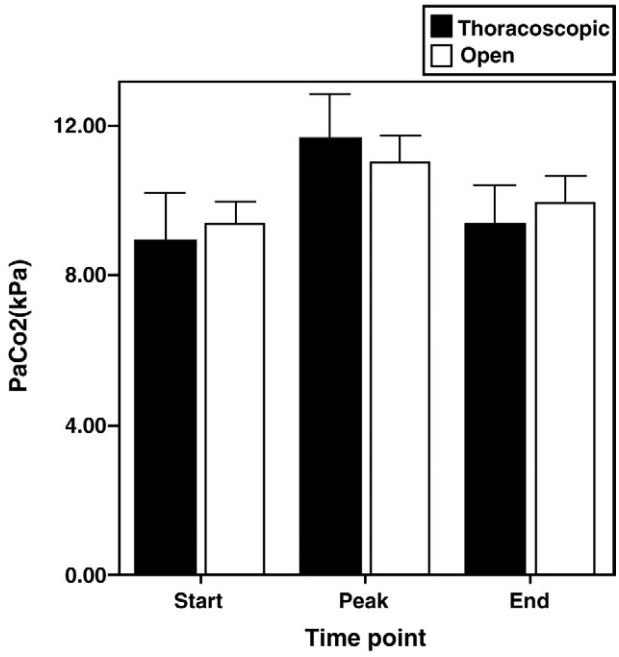

Fig. 2 $PaCO_2$ levels during thoracoscopic and open repair of CDH. Bars represent mean, and error bars represent SEM. Peak levels were defined as the highest value recorded intraoperatively.

Duration of operation (excluding anesthesia) was longer in thoracoscopic group compared with open repair (Table 1). Five neonates who had thoracoscopy were converted to open repair (38%), 4 were converted because of surgical difficulties, and 1 was converted due to intraoperative O_2 desaturation. All 5 then had an uneventful open repair. Two patients converted from thoracoscopic to open procedure also had a Ladd procedure for intestinal malrotation. Length of operation in the group completed thoracoscopically was 2.9 ± 0.4 compared to 3.9 ± 0.5 hours for those converted to open. Data from these patients initially treated thoracoscopically were included in the thoracoscopic group for the duration of thoracoscopic surgery and CO_2 insufflation. Patch repair was used in 12 (34%) open and 6 (46%) thoracoscopic repairs.

$EtCO_2$ was significantly changed in both open ($P = .009$) and thoracoscopic ($P = .02$) groups (Fig. 1). Peak $EtCO_2$ was significantly higher in the thoracoscopic group compared with the open (Table 2).

There was no significant change in $PaCO_2$ (Fig. 2) over time in either the open ($P = .21$) or thoracoscopic ($P = .22$) groups. In contrast to the significant difference in peak $EtCO_2$ between groups, there was no significant difference in

Table 2 $EtCO_2$, arterial blood pH, and $PaCO_2$ between open and thoracoscopic groups (mean ± SEM)

	Open (n = 35)	Thoracoscopy (n = 13)	*P*
Maximum $EtCO_2$ (kPa)	6.55 ± 0.49	8.38 ± 0.30	.003
Mean $EtCO_2$ (kPa)	5.67 ± 0.23	7.05 ± 0.48	.006
Lowest pH	7.14 ± 0.03	7.16 ± 0.06	.89
Mean pH	7.20 ± 0.03	7.21 ± 0.04	.66
Maximum $PaCO_2$ (kPa)	10.94 ± 0.07	10.53 ± 1.16	.65
Mean $PaCO_2$ (kPa)	9.76 ± 0.57	9.94 ± 0.97	.88

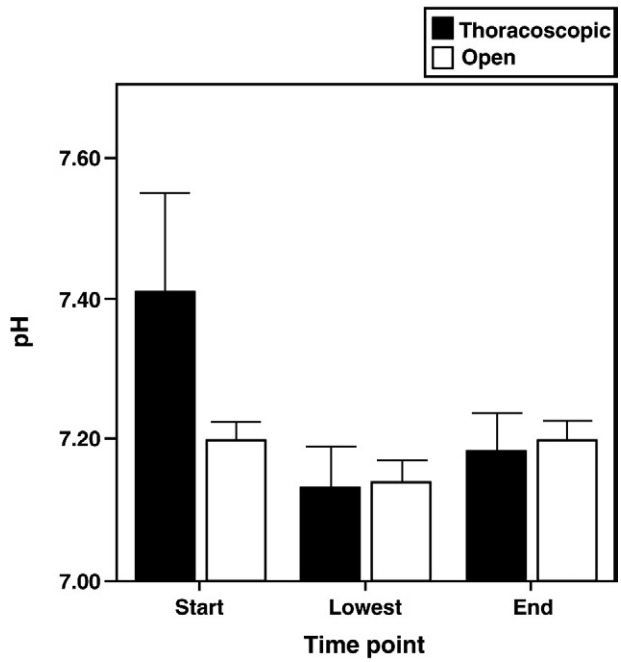

Fig. 3 Arterial pH during thoracoscopic and open repair of CDH. Bars represent mean, and error bars represent SEM. Lowest levels were defined as the lowest pH recorded intraoperatively.

the peak in $Paco_2$ between open and thoracoscopic groups intraoperatively (Table 2).

Likewise, there was no significant overall change in pH (Fig. 3) in either the open ($P = .26$) or the thoracoscopic ($P = .1$) groups, with no difference in the lowest recorded pH or the mean pH (Table 2) between groups intraoperatively.

The median follow-up was 31 months (range, 5-84 months) after open repair and 15 months (range, 1-40 months) after thoracoscopic repair. There were 3 (8%) of 40 recurrences after open repair and 2 (25%) of 8 recurrences after thoracoscopic repair ($P = .19$). Two of these recurrences (1 open and 1 thoracoscopic) occurred after patch repair. There was no significant difference in the rate of recurrence in those with patch and those without patch repair ($P = .90$). Five in the open group had Ladd procedure done at surgery. Three in the open group presented with presumed adhesive intestinal obstruction at 3 months after the primary procedure (range, 1-14 months); 1 had laparotomy and adhesiolysis. No patient in the thoracoscopic group presented with intestinal obstruction.

3. Discussion

We describe our experience with thoracoscopic repair of CDH at our institution with special reference to intraoperative CO_2 handling compared with the open operation. There was a significant increase in $EtCO_2$ in both the open and thoracoscopic groups, but peak levels were significantly higher in the thoracoscopic group. There was no significant difference in the peak $Paco_2$ between groups; both mean and lowest pH were also comparable between groups. We also observed a high rate of hernia recurrence, but a lower incidence of adhesional intestinal obstruction after thoracoscopic repair; this needs further evaluation. Although this was not a randomized trial, both groups were comparable with regard to demographic data and clinical status at the time of operation.

Increased CO_2 absorption during thoracoscopy is generally well tolerated in infants and children. However, there are instances where extra vigilance is required. Younger, smaller children have been shown to have larger changes in $EtCO_2$ and/or CO_2 elimination during both laparoscopy [11] and thoracoscopy [8]. Neonates are therefore particularly vulnerable. In CDH, the persistent pulmonary hypertension, lung hypoplasia, and pulmonary vasculature hyperactivity, which accompany the disease, are additional confounding factors in the management of the increased CO_2 load. Any significant acidosis may increase shunting and worsen any pulmonary hypertension with deleterious effects on systemic perfusion pressures, ventilation, and oxygenation.

Recently, Bliss et al [12] reported their experience of CO_2 management during thoracoscopic CDH repair in neonates. In their study, $EtCO_2$ increased to a maximum of 64 ± 13 Torr (8.5 ± 1.7 kPa); this is comparable with levels reported in this study. Mean highest $Paco_2$ in their study was 10.4 ± 3.9 was again similar to our findings. Finally, they found that there was a dissociation between $EtCO_2$ and $Paco_2$, with $EtCO_2$ underestimating $Paco_2$. This underestimation was not reflected in our experience. We found that there was a significant elevation of $EtCO_2$ without a significant increase in $Paco_2$ or decrease in pH. Therefore, in our cohort, $EtCO_2$ seemed to overestimate $Paco_2$. However, in this retrospective review, it is difficult to make definitive conclusions because the exact timing of recordings did not always coincide. This is one flaw of our analysis and a possible explanation for the differences noted in this study compared with that of Bliss et al [12]. We support the notion that both blood gases and $EtCO_2$ should be monitored and correlated in these patients, especially when significant changes in $EtCO_2$ are noted. A prospective controlled study with a protocol of regular pH measurements, along with end-tidal, transcutaneous, and arterial CO_2 measurements, is needed to investigate handling of the CO_2 load and systemic effects of hypercapnia in CDH patients.

The pathophysiologic effects of capnothorax, hypercapnia, and hypoxia intraoperatively are complex. Gentili et al [4] demonstrated an increase in $EtCO_2$ during thoracoscopy in children, with associated decrease in systolic and diastolic blood pressure. Mukhtar et al [5] suggested a beneficial effect of hypercapnia by increasing cardiac output in a group of children having thoracoscopic patent ductus ligation. The balance of cardiovascular effects in the presence of persistent pulmonary hypertension in CDH is not clear. Thoracoscopic repair of CDH has been shown to be well documented in the literature [1,12]. There seems to be a trend to allowing a "permissive hypercapnia" intraoperatively [12], similar to the concept during preoperative stabilization. However, the limits of such permissive hypercapnia have not been established intraoperatively.

Also, there are concerns about the effect of hypercapnia on systemic circulation and cerebral perfusion. Although one study on neonatal piglets demonstrated efficient autoregulation at the pulmonary level during 1-lung ventilation [13], the effects on cerebral perfusion have not been fully investigated. Hypercapnia may alter cerebral metabolism independent of any effect on brain oxygenation. When neonatal piglets were well oxygenated but exposed to increasing levels of CO_2 for 6 hours, there was decreased adenosine triphosphate generation, phosphorylation of transcription factors, and increased apoptosis in the brain [14]. It is therefore worth considering the effects of CO_2 on cerebral metabolism and oxygenation, even though there have been few documented adverse effects of CO_2 insufflation during thoracoscopy in CDH patients. Safety with regard to the added concerns with CO_2 capnothorax during thoracoscopy is particularly important in CDH patients that are known to have significant long-term neurologic consequences [15,16].

At a first glance, our recurrence rate after thoracoscopic repair (25%) seemed higher than our historical controls (8%); however, this failed to reach statistical significance possibly

because of the smaller number of infants undergoing thoracoscopic repair. However, continued vigilance is needed to detect differences in the longer term. The recurrence rate of 25% after thoracoscopic repair seen in this series is comparable with that reported in the recent literature [17,18]. Possible explanations for higher recurrences during thoracoscopic approach include the acquiring of the learning curve for the procedure, the use of patch repair during thoracoscopy, and technical difficulties in achieving a complete diaphragmatic closure in these neonates. We only embarked on thoracoscopic repairs after establishing laparoscopy at our center for more than 10 years. Two of the recurrences after thoracoscopic repair occurred early in the series and further technical lessons have been put into practice to hopefully decrease this possible causative factor. Only 1 recurrence occurred with a patch repair, of 6 total patch repairs performed thoracoscopically. The costophrenic angle is an anatomical area that does not lend itself to easy intracorporeal suturing in very small neonates. Extra vigilance is required when closing the diaphragmatic defect in this area. There was no obvious major technical problem identified at re-do surgery. We continue to follow up these patients to identify the approach associated with the best short- and long-term outcome for patients.

Despite the disadvantages discussed above, this study indicates that intestinal obstruction did not occur after thoracoscopic repair. This can be because of minimal handling of herniated intestine and lack of adhesion formation. This finding needs to be proven by longer term follow-up study. In addition, as indicated by other prospective studies [19], postoperative pain is reduced and cosmesis seems superior after minimally invasive surgery.

Although we did not demonstrate any difference in blood gas analysis between the 2 approaches in this study, regular blood gas analysis was not routinely performed and was done as deemed necessary. However, there was a significant change in $EtCO_2$, which may be more representative and accurate as it was continuously monitored. We therefore think that a prospective, randomized study is needed. This should include a protocol of regular monitoring of CO_2 metabolism along with systemic and cerebral perfusion during thoracoscopy to complete the qualitative assessment, to help with clinical governance and monitor outcome in these children both in the short-term and for long-term outcome.

Acknowledgments

We wish to acknowledge the contribution of Mittal Foundation in supporting this study.

References

[1] Ponsky TA, Rothenberg SS. Minimally invasive surgery in infants less than 5 kg: experience of 649 cases. Surg Endosc 2008;22:2214-9.
[2] Pacilli M, Pierro A, Kingsley C, et al. Absorption of carbon dioxide during laparoscopy in children measured using a novel mass spectrometric technique. Br J Anaesth 2006;97:215-9.
[3] Arca MJ, Barnhart DC, Lelli JL, et al. Early experience with minimally invasive repair of congenital diaphragmatic hernias: results and lessons learned. J Pediatr Surg 2003;38:1563-8.
[4] Gentili A, Lima M, De RR, et al. Thoracoscopy in children: anaesthesiological implications and case reports. Minerva Anestesiol 2007;73:161-71.
[5] Mukhtar AM, Obayah GM, Elmasry A, et al. The therapeutic potential of intraoperative hypercapnia during video-assisted thoracoscopy in pediatric patients. Anesth Analg 2008;106:84-8.
[6] Haynes SR, Bonner S. Review article: anaesthesia for thoracic surgery in children. Paediatr Anaesth 2000;10:237-51.
[7] Cheng KI, Tang CS, Tsai EM, et al. Correlation of arterial and end-tidal carbon dioxide in spontaneously breathing patients during ambulatory gynecologic laparoscopy. J Formos Med Assoc 1999;98:814-9.
[8] McHoney M, Mackinlay G, Munro F, et al. Effect of patient weight and anesthetic technique on CO_2 excretion during thoracoscopy in children assessed by end-tidal CO_2. J Laparoendosc Adv Surg Tech A 2008;18:147-51.
[9] Stolar CJH. Congenital diaphragmatic hernia. In: Spitz L, Coran AG, editors. Operative pediatric surgery. London, UK: Hodder Arnold; 2006. p. 153-8.
[10] Rothenberg S. Thoracoscopic CDH repair. In: Holcomb III GW, Georgeson KE, Rothenberg SS, editors. Atlas of pediatric laparoscopy and thoracoscopy. Philadelphia: PA Saunders Elsevier; 2009. p. 241-6.
[11] McHoney M, Corizia L, Eaton S, et al. Carbon dioxide elimination during laparoscopy in children is age dependent. J Pediatr Surg 2003;38:105-10.
[12] Bliss D, Matar M, Krishnaswami S. Should intraoperative hypercapnea or hypercarbia raise concern in neonates undergoing thoracoscopic repair of diaphragmatic hernia of Bochdalek? J Laparosc Adv Surg Tech 2009;19:S55-8.
[13] Tonz M, Bachmann D, Mettler D, et al. Pulmonary function after one-lung ventilation in newborns: the basis for neonatal thoracoscopy. Ann Thorac Surg 1998;66:542-6.
[14] Fritz KI, Zubrow A, Mishra OP, et al. Hypercapnia-induced modifications of neuronal function in the cerebral cortex of newborn piglets. Pediatr Res 2005;57:299-304.
[15] Davis PJ, Firmin RK, Manktelow B, et al. Long-term outcome following extracorporeal membrane oxygenation for congenital diaphragmatic hernia: the UK experience. J Pediatr 2004;144:309-15.
[16] Lally KP, Engle W. Post discharge follow-up of infants with congenital diaphragmatic hernia. Pediatrics 2008;121:627-32.
[17] Cho SD, Krishnaswami S, McKee JC, et al. Analysis of 29 consecutive thoracoscopic repairs of congenital diaphragmatic hernia in neonates compared to historical controls. J Pediatr Surg 2009;44:80-6.
[18] Guner YS, Chokshi N, Aranda A, et al. Thoracoscopic repair of neonatal diaphragmatic hernia. J Laparosc Adv Surg Tech 2008;18:875-80.
[19] Hall NJ, Pacilli M, Eaton S, et al. Recovery after open versus laparoscopic pyloromyotomy for pyloric stenosis: a double-blind multicentre randomised controlled trial. Lancet 2009;373:390-8.