Continuous negative extrathoracic pressure in children after congenital heart surgery

Nobuaki Shime, Chiaki Toida,
Toshiyuki Itoi and Satoru Hashimoto

ABSTRACT

Objective: To study the effects of continuous negative extrathoracic pressure (CNEP) in children after surgery for congenital heart defects.

Methods: We applied - 3 to - 6 cmH_2O CNEP with a cuirass and ventilator to 16 infants and children managed in a paediatric intensive care unit after surgery for congenital heart defects between July 2003 and July 2004. Changes in haemodynamics and gas exchange were assessed 1h and 8h after CNEP application. All patients were breathing spontaneously after successful extubation while receiving CNEP.

Results: Patients were aged 1–34 months (median, 11.5 months). Six had undergone right heart bypass surgery (Group A), and 10 had received positive pressure ventilation for >48h after other types of heart surgery (Group B). Urine output increased significantly, by 49% at 1h in Group A, and by 65% in Group B. Decreases in central venous pressure, from median (range) of 15 (12–22)mmHg to 12 (10–21) mmHg in Group A, and from 9 (5–13)mmHg to 8.5 (5–12)mmHg in Group B, and tendency to increases in arterial blood pressure were observed after 1h. In Group B, oxygen saturation increased from 96.5% (84%–100%) at baseline to 99% (87%–100%) and 100% (88%–100%) at 1h and 8h, respectively.

Conclusion: Prophylactic application of CNEP immediately after extubation appears to decrease right ventricular load and improve arterial oxygenation. CNEP might become a useful option in the management of congenital heart surgery patients.

Crit Care Resusc 2006; 8: 297–302

See also page 339

Negative pressure ventilation was developed as an effective non-invasive alternative to positive pressure ventilation. Studies performed before the early 1990s reported the beneficial effects of a negative pressure chamber system, similar to the historic "iron lung".[1] Continuous negative extrathoracic pressure (CNEP) with a negative pressure chamber has been associated with improvements in respiratory function in newborn infants, with reduced need for oxygen and positive pressure ventilation.[2]

In the late 1990s, an extracorporeal cuirass was developed as the next generation of negative pressure systems. Negative pressure ventilation exerts positive haemodynamic effects by decreasing pulmonary vascular resistance and right ventricular afterload in patients with congenital heart defects. The delivery of –18 to –22 cmH_2O inspiratory pressure by a Hayek oscillator significantly increased cardiac output early after tetralogy of Fallot[3,4] and Fontan[5] operations, and even in children with normal cardiac function.[6]

A biphasic, cuirass negative-pressure RTX ventilator (Medivent, London, UK) recently became available in our clinical practice. We describe our experience using this ventilator in the management of infants and children after cardiac surgery.

Methods

We studied a consecutive series of infants and children admitted after surgery for congenital cardiac defects to the Paediatric Intensive Care Unit of Kyoto Prefectural University Children's Hospital, Japan. Two groups were included in the study over 6-month periods:

- patients who underwent right heart bypass surgery between July 2003 and January 2004 (Group A); and
- patients who underwent other types of congenital heart surgery and required >48 hours of ventilator support postoperatively between January and July 2004 (Group B).

The institutional review board of Kyoto Prefectural University of Medicine approved this study, and written, informed consent to participate was obtained from the patients' parents.

Continuous negative extrathoracic pressure

The RTX ventilator comprises an extrathoracic cuirass attached to a small ventilator. A cuirass of appropriate size for each individual (usually size 1 for neonates, 2 for infants and 3 for small children) was placed on the chest and upper abdomen and fixed with a strap (Figure 1).

CNEP delivering up to –6 cmH_2O of negative pressure was applied after withdrawal of positive pressure ventilation and confirmation of successful extubation by physical observation over at least 1 hour and blood gas analysis. Patients

Figure 1. Application of continuous negative extrathoracic pressure

The RTX ventilator comprises an extrathoracic cuirass attached to a small ventilator. The cuirass is placed on the chest and upper abdomen and fixed with a strap. ◆

breathed spontaneously with continuous nasal O_2 (usually 1–2 L/min) provided as necessary, remaining unchanged throughout the study period. CNEP was scheduled to be delivered for at least 8 hours, with brief interruptions for nursing care and position changes. The decision to end CNEP was left to the attending physician. Patients underwent routine intensive care monitoring, including measurement of mean arterial pressure (MAP), superior vena cava pressure (SVCP), heart rate, arterial O_2 saturation by pulse oximetry, blood gas analysis and urinary output.

Data analysis

We assessed haemodynamic and gas exchange variables before application of CNEP and 1 h and 8 h later. Variables comprised heart rate, MAP, SVCP, arterial lactate level, urinary output and pulmonary gas exchange, including arterial O_2 saturation and $PaCO_2$. Data are expressed as means ± standard deviation (SD) or medians (range). The changes in variables from baseline were examined in each patient subgroup. Wilcoxon's non-parametric test was used to examine within-group differences in sequential data. A P value < 0.05 was considered significant. Statistical analyses were performed using Statview 5.0 for Macintosh (SAS Institute, Cary, NC, USA).

Results

Patient characteristics

Patients were aged 1–34 months (median, 11.5 months) and comprised 10 girls and six boys, with body weight 3.4–11.3 kg (median, 6.8 kg). Group A comprised six patients: four had undergone extracardiac cavopulmonary connection, and two Glenn anastomoses procedures. Group B comprised 10 patients: four had undergone closures of ventricular septal defects, four total repair of tetralogy of Fallot or pulmonary stenosis, and two palliative operations, comprising Blalock–Taussig shunt and pulmonary arterial banding, respectively. In Group B, the median duration of positive pressure ventilation before beginning CNEP was 6 days.

Continuous negative extrathoracic pressure

CNEP was applied for 20 ± 14 h in Group A, and 22 ± 12 h in Group B, at negative pressures of 4.3 ± 1.2 cmH_2O and 4.9 ± 0.6 cmH_2O, respectively. CNEP was discontinued at 6 h in one patient in Group A and two patients in Group B, because of discomfort or nursing or medical care issues. Therefore, data for 6 h were used for the 8 h analysis in these three patients. Except for a single case of mild skin erosion around the cuirass seal, CNEP was uncomplicated; all patients were weaned uneventfully, and none were reintubated.

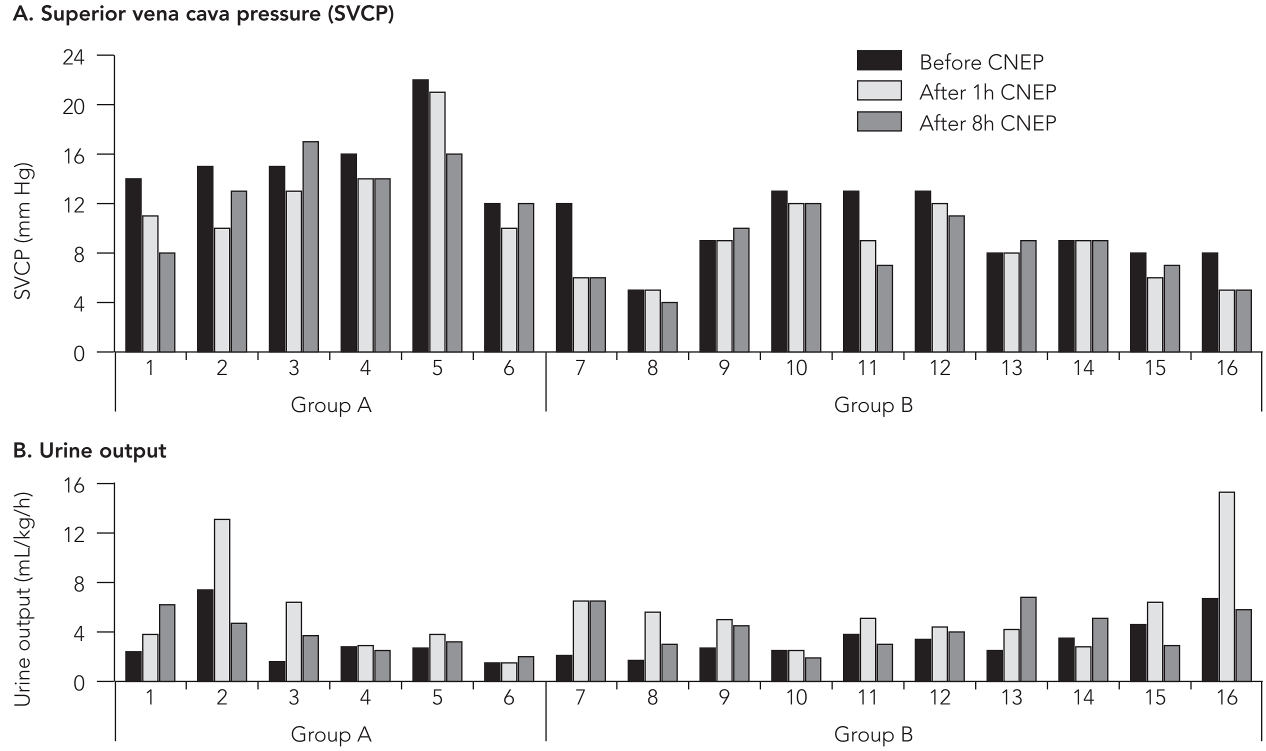
Haemodynamic measurements

There were significant decreases in SVCP in Group A, from a median (range) of 15 (12–22) mmHg before CNEP application to 12 (10–21) mmHg after 1 hour of CNEP ($P = 0.02$), and statistically significant but not clinically relevant changes in SVCP in Group B (Table 1). Patients with higher SVCP levels (> 12 mmHg) tended to have decreases in SVCP after CNEP application (Figure 2A). Trends of increasing MAP were observed in both groups. Arterial lactate level did not change significantly. In addition, a significant increase in urine output was observed in both groups: from a median (range) of 2.55 (1.5–7.4) mL/kg/h at baseline to 3.8 (1.5–13.1) mL/kg/h at 1 h (49% increase) in Group A ($P = 0.04$); and from 3.1 (1.7–6.7) mL/kg/h to 5.1 (2.5–15.3) mL/kg/h at 1 h (65% increase) in Group B ($P = 0.01$). Patients with lower urine output before CNEP (< 2 mL/kg/h) tended to have the largest increases — up to threefold (Figure 2B).

Pulmonary gas exchange

Arterial O_2 saturation increased significantly in Group B, from a median (range) of 96.5% (84%–100%) at baseline,

Figure 2. Superior vena cava pressure and urine output in individual patients before and after application of continuous negative extrathoracic pressure (CNEP)



to 99% (87%–100%) at 1 h ($P = 0.05$), and 100% (88%–100%) at 8 h ($P = 0.01$), while no change was observed in $PaCO_2$ (Table 1).

Discussion

We found that prophylactic application of CNEP in infants and children ceasing positive pressure ventilation offered immediate and effective cardiopulmonary support, manifesting as an increase in urinary output and arterial oxygenation, and a decrease in SVCP. Contributing factors might be the effect of negative pressure on pulmonary function, characterised by increased alveolar recruitment from lung expansion, decrease in pulmonary vascular resistance by negative intrathoracic pressure, or both.[7]

To our knowledge, this is the first study to show significantly positive cardiorespiratory effects of CNEP in a paediatric population. Although we did not measure

Table 1. Cardiorespiratory parameters before and during application of continuous negative extrathoracic pressure in 16 infants and children (values are median and range)

	Group A			Group B		
Parameter	Before	1 hour	8 hours	Before	1 hour	8 hours
Heart rate (beats per min)	132 (120–150)	130 (126–150)	124 (120–150)	155 (130–183)	160 (120–181)	157 (98–183)
Mean arterial pressure (mmHg)	66 (50–93)	73 (65–93)	74 (69–80)	68 (57–91)	73.5 (64–100)	77.5 (57–99)
Superior vena cava pressure (mmHg)	15 (12–22)	12* (10–21)	13.5 (8–17)	9 (5–13)	8.5* (5–12)	8† (4–12)
Arterial oxygen saturation (SpO_2) (%)	92 (82–100)	94 (82–99)	93 (83–100)	96.5 (84–100)	99‡ (87–100)	100‡ (88–100)
$PaCO_2$ (mmHg)	35 (31–41)	37.5 (32–49)	40 (34–47)	41.5 (32–55)	40 (29–54)	46 (30–50)
Arterial lactate level (mmoL/L)	1.45 (0.9–3.9)	1.5 (0.8–2.5)	1.55 (0.5–2.2)	0.85 (0.5–3.1)	0.9 (0.5–3.2)	0.8 (0.4–1.7)
Urine output (mL/kg/h)	2.55 (1.5–7.4)	3.8† (1.5–13.1)	3.45 (2–6.2)	3.05 (1.7–6.7)	5.05‡ (2.5–15.3)	4.25 (1.9–6.8)

* P=0.02, † P=0.04, ‡ P=0.01, for comparison with "before" value.

cardiac output directly, because of its invasive nature, the significant increase in urine output and decrease in SVCP suggest an improvement in ventricular performance. Prophylactic use of CNEP in infants and children with limited pulmonary or haemodynamic reserve might facilitate their successful transition after extubation.

Negative pressure ventilation for haemodynamic support in children who have undergone surgery for congenital heart disease has been described by Shekerdemian et al.[3-6] In their reports, negative pressure mandatory ventilation with –18 to –22 cmH_2O was compared with positive pressure ventilation at a maximum inspiratory pressure of 16 to 20 cmH_2O. A significant 28% increase in cardiac output after simple cardiac surgery, and an 11% increase in healthy children, was observed during a 15-minute treatment application.[6] Patients with critically low right-ventricular performance caused by limited pulmonary vascular compliance, who had undergone repair of tetralogy of Fallot or right heart bypass surgery, appeared to benefit most from negative extrathoracic pressure.[3-5] A marked increase in pulmonary blood flow (39% at 15 minutes and 67% at 45 minutes) was observed in patients with tetralogy of Fallot.[3] Similarly, cardiac output increased by 46% in the group of patients who had undergone right heart bypass surgery.[5] Shekerdemian et al also recently reported the successful longer application of negative pressure ventilation for rescue from a low cardiac output state.[4] We observed similar haemodynamic effects of CNEP after right heart bypass and other cardiac operations, including in haemodynamically stable patients. In addition, our observations suggest that the application of CNEP alone, without negative pressure mandatory ventilation, might be sufficient to offer significant right ventricular support in patients who are breathing spontaneously. The positive effects of CNEP on cardiac output reported in mechanically ventilated adult patients[8] were also suggested in our study. As the application of synchronised negative pressure ventilation can be problematic in children who breathe spontaneously at a rapid rate, the easier CNEP mode seems a sensible choice.

The positive effects observed in the group of children who had been ventilated for longer than 48 hours suggest also that CNEP is an alternative non-invasive method of ventilation for patients whose condition remains unstable after extubation. Experimental studies have shown that CNEP has equivalent effects to continuous positive airway pressure on lung mechanics and gas exchange. In a piglet model of saline-lavage[9] or endotoxin-induced lung injury,[10] CNEP and positive end-expiratory pressure (PEEP) had similar effects on end-expiratory lung volume or arterial oxygenation. Likewise, in adults presenting with acute lung injury, –20 cmH_2O CNEP and 15 cmH_2O PEEP had similar effects on lung mechanics. In addition, CNEP was associated with less compromise of haemodynamic function than PEEP.[11] These haemodynamic advantages make CNEP a preferred choice for non-invasive postoperative respiratory support of children with cardiac defects.

Earlier clinical studies using a negative pressure chamber have suggested therapeutic respiratory effects conferred by CNEP in paediatric and neonatal populations.[1,2] Prophylactic use of CNEP decreased the need for O_2 or ventilators in neonates,[1] as well as the need for O_2 in infants with bronchiolitis.[2] However, the chamber system is more difficult to operate, increasing the demands on nursing care, and has now been replaced by superior nasal continuous positive airway pressure systems. The new CNEP system used in this study comprises a simple extrathoracic cuirass and a small ventilator. With the easy implementation of the new extracorporeal cuirass, CNEP might become a useful clinical option for non-invasive ventilation.

Conclusions

In this consecutive series of children who had undergone various operations for congenital heart defects, the application of CNEP using an extrathoracic cuirass during spontaneous breathing after extubation appeared to improve haemodynamic function and pulmonary gas exchange. However, this study is limited by the lack of a control group. The reported improvements could have been the natural history after successful extubation and not due to the CNEP treatment. The safety and efficacy of prophylactic application of CNEP should be proven by more extensive studies with control groups who are not treated with CNEP.

Author details

Nobuaki Shime, Vice-Director, Intensive Care Division, Pediatric Intensive Care Division, and Assistant Professor, Department of Anesthesiology and Intensive Care[1]

Chiaki Toida, Clinical Fellow, Department of Anesthesiology and Intensive Care[2]

Toshiyuki Itoi, Associate Professor, Department of Pediatric Cardiology[1]

Satoru Hashimoto, Director, Intensive Care Division, and Professor, Department of Anesthesiology and Intensive Care[1]

1 University Hospital, Kyoto Prefectural University of Medicine, Kyoto, Japan.

2 National Children's Hospital, Tokyo, Japan.

Correspondence: shime@koto.kpu-m.ac.jp

References

1 Shah PS, Ohlsson A, Shah JP. Continuous negative extrathoracic pressure or continuous positive airway pressure for acute hypoxemic respiratory failure in children. *Cochrane Database Syst Rev* 2005; 20: CD003699.

2 Samuels MP, Raine J, Wright T, et al. Continuous negative extrathoracic pressure in neonatal respiratory failure. *Pediatrics* 1996; 98: 1154-60.

3 Shekerdemian LS, Bush A, Shore DF, et al. Cardiorespiratory responses to negative pressure ventilation after tetralogy of fallot repair: a hemodynamic tool for patients with a low-output state. *J Am Coll Cardiol* 1999; 33: 549-55.

4 Shekerdemian LS, Schulze-Neick I, Redington AN, et al. Negative pressure ventilation as haemodynamic rescue following surgery for congenital heart disease. *Intensive Care Med* 2000; 26: 93-6.

5 Shekerdemian LS, Shore DF, Lincoln C, et al. Negative-pressure ventilation improves cardiac output after right heart surgery. *Circulation* 1996; 94: II49-55.

6 Shekerdemian LS, Bush A, Lincoln C, et al. Cardiopulmonary interactions in healthy children and children after simple cardiac surgery: the effects of positive and negative pressure ventilation. *Heart* 1997; 78: 587-93.

7 Thomson A. The role of negative pressure ventilation. *Arch Dis Child* 1997; 77: 454-8.

8 Torelli L, Zoccali G, Casarin M, et al. Comparative evaluation of the haemodynamic effects of continuous negative external pressure (CNEP) and positive end-expiratory pressure (PEEP) in mechanically ventilated trauma patients. *Intensive Care Med* 1995; 21: 67-70.

9 Easa D, Mundie TG, Finn KC, et al. Continuous negative extrathoracic pressure versus positive end-expiratory pressure in piglets after saline lung lavage. *Pediatr Pulmonol* 1994; 17: 161-8.

10 Mundie TG, Finn K, Balaraman V, et al. Continuous negative extrathoracic pressure and positive end-expiratory pressure. A comparative study in *Escherichia coli* endotoxin-treated neonatal piglets. *Chest* 1995; 107: 249-55.

11 Borelli M, Benini A, Denkewitz T, et al. Effects of continuous negative extrathoracic pressure versus positive end-expiratory pressure in acute lung injury patients. *Crit Care Med* 1998; 26: 1025-31. ❑