Non-invasive aortic blood flow measurement in infants during repair of craniosynostosis†


Summary
We have assessed the potential clinical benefit of a new echo-Doppler device (Dynemo 3000) which provides a continuous measure of aortic blood flow (ABF) using an aortic flowmeter and a paediatric oesophageal probe, during repair of craniosynostosis in infants under general anaesthesia. The data recorded included: ABFi (indexed to body surface area), stroke volume (SVi), systemic vascular resistance (TSVRi), pre-ejection period (PEP), left ventricular ejection time (LVET), mean arterial pressure (MAP), heart rate (HR) and central venous pressure (CVP). Data were collected: before (T1) and 3 min after skin incision (T2), at the time of maximal haemorrhage (T3) and at the end of the procedure (T4). Twelve infants (aged 7.0 (range 6–12) months) were included. ABFi, MAP and CVP were significantly lower at T3 compared with T1 (2.0 (0.8) vs 3.0 (0.8) litre min\(^{-1}\) m\(^{-2}\); 46.1 (5.8) vs 65.2 (8.9) mm Hg and 2.8 (1.6) vs 5.2 (2.1) mm Hg; \(P<0.05\)). PEP/LVET ratio was significantly lower at T2 compared with T1 (0.25 (0.05) vs 0.30 (0.06)) and increased at T4 (0.36 (0.04); \(P<0.05\)).

These preliminary results suggest that this non-invasive ABF echo-Doppler device may be useful for continuous haemodynamic monitoring during a surgical procedure associated with haemorrhage in infants. (Br. J. Anaesth. 1998; 81: 696–701).

Keywords: complications, craniosynostosis; blood, flow; measurement techniques, ultrasound; anaesthesia, paediatric

Craniosynostosis is a relatively common disorder, with an estimated incidence of 1 per 2000 live births, related to premature closure of skull sutures.\(^1\) An early surgical correction is mandatory in the majority of cases because the compensatory deformation of the skull which occurs during rapid growth of the brain in early infancy may lead to increased intracranial pressure, especially in children older than 1 yr of age, and particularly if multiple sutures are involved.\(^3\) Surgery is aimed at restoring normal anatomy at an early age to achieve the best cosmetic result and avoid possible cerebral consequences.\(^24\)

Therefore, surgical procedures for correction of craniosynostosis are performed in young infants with a small blood volume and represent major surgery with extensive blood loss.\(^56\)

Accurate determination and precise restoration of blood losses represent the major concern for the anaesthetist during this surgery. However, intraoperative assessment of blood loss is difficult and requires precise haemodynamic monitoring. Although it has been argued that invasive measurement of cardiac output allows earlier interventions during critical surgical procedures, the technical difficulties of inserting balloon catheters into small children are such that haemodynamic evaluation frequently relies solely on clinical monitoring (heart rate, arterial pressure, pulse oximetry and \(P_{\text{ACO}_{2}}\)). Unfortunately, clinical assessment of cardiac function using these measurements has been shown to be unreliable in children.\(^7\)

Experience with intraoperative transoesophageal echocardiography is limited in children,\(^8\) and this monitoring is not widely available for infants. Moreover, the data provided by cardiac echocardiography only allow a diagnosis of a cardiovascular status at a given moment during the perioperative period.

These factors encouraged the development of non-invasive ultrasound techniques to measure cardiac output in newborns and infants. The oesophageal route was first used in an attempt to overcome the problems noted with the suprasternal route\(^9\) and was progressively developed and improved by INSERM (U281) in France.\(^1011\) Application of this methodology in adults during general anaesthesia and in intensive care patients revealed the clinical usefulness of aortic blood measurement.\(^12\) Non-invasive haemodynamic monitoring can now be performed with an echo-Doppler aortic blood flowmeter (Dynemo 3000 Sometic Inc., France). A miniaturized probe has been developed to continuously measure descending thoracic aortic diameter and blood velocity simultaneously, in infants as in adults. The aim of our preliminary study was to assess the feasibility and likely clinical benefits of continuous measurement of aortic blood flow (ABF) during repair of craniosynostosis, a surgical procedure associated with significant haemorrhage.

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Patients and methods

After obtaining approval from the Ethics Committee and informed consent from parents, we studied prospectively 12 infants (aged 6 months to 1 yr), ASA I–II, with a body weight of 6–12 kg, undergoing surgical repair of craniosynostosis. Exclusion criteria were: known or suspected oropharyngeal, oesophageal, aortic or mediastinal pathology; severe gastro-oesophageal reflux; or known or suspected latex sensitization.

All procedures were performed under general anaesthesia without induced hypotension after skull skin infiltration with epinephrine (adrenaline) 1:200 000 in normal saline. After premedication with clorazepate dipotassium, general anaesthesia was induced with 2–3% halothane followed by fentanyl 5 μg kg \(^{-1}\). Neuromuscular block was achieved with atracurium 0.5 mg kg \(^{-1}\). After orotracheal intubation, general anaesthesia was maintained using continuous i.v. infusion of fentanyl and controlled ventilation with 0.8–1.5% isoflurane and 50% nitrous oxide in oxygen. Monitoring included continuous ECG, invasive arterial and central venous pressures, core temperature, pulse oximetry, end-tidal carbon dioxide concentration and urine output.

Preoperative blood samples were obtained for measurement of red blood cells, platelet count, haemoglobin concentration, packed cell volume (PCV) and coagulation screen. Serial blood samples were obtained at least every 2 h during operation and as frequently as clinically indicated, for measurement of blood-gas tensions and PCV. Intraoperative management was as described previously. Briefly, an isovolaemic compensation of blood loss was strictly observed, with fluid replacement based on haemodynamic variables, and including human serum albumin, colloids and packed red blood cells in order to maintain PCV in the range 0.28–0.35. Fresh frozen plasma was used only in patients requiring more than 70% of estimated blood volume transfusion.

MEASUREMENT PRINCIPLE

Velocity is measured using the Doppler formula: \(v = \frac{(C_x \Delta f/2Fe)(x \cos I)}{I}\) where \(C_x\) = ultrasound velocity inside the blood, \(\Delta f\) = frequency variation of emitted ultrasound, \(Fe\) = emission frequency, and \(I\) = angle of incidence and reflection of ultrasound against the red cells. Determination of ABF requires simultaneous and continuous measurement of the aortic section and blood velocity inside the aorta, at the same anatomical level where the aorta and oesophagus are nearly parallel. Using the specially designed ultrasound paediatric probe introduced into the oesophagus, we measured the diameter of the descending thoracic aorta using an M-mode echographic system and blood flow velocity with a pulsed Doppler velocimeter.

PROBE AND FLOWMETER

The paediatric oesophageal probe has two ultrasound transducers (3x3 mm) located at the distal part of the probe. The first operates at 10 MHz M-echo mode scanner, perpendicular to the centre line. The second is a Doppler pulsed emission transducer operating at 5 MHz and mounted at an angle of 60° to the centre line of the probe: the pulsed Doppler is emitted with a 48° divergent beam and the gated Doppler signal depth is adapted automatically to the aortic wall location values. This small probe, specially designed for newborns and infants, measures 5 mm (external diameter) and is 45 cm long. For infants, an 8–12-mm diameter cylindrical latex balloon is mounted on the sheath ready to be filled with 0.5 or 2 ml of water. This inflated balloon which surrounds the transducer maintains a constant angle of incidence of the ultrasound beams and allows the captor to rotate freely inside it without contact against the oesophageal mucosal wall. The balloon ensures transmission of ultrasound waves without air interposition and dissipates any heat produced.

The oesophageal probe was inserted and positioned immediately after induction of anaesthesia. Depth of introduction of the probe into the oesophagus varied according to the height of the infant and was measured between the echo transducer placed on the third intercostal juxtaexternal space and a slide rubber ring placed at the level of the mouth. This distance approximated the level where the aorta and oesophagus are parallel.

The flowmeter includes three main parts: M-mode imaging system for diameter measurement, pulsed Doppler for velocity measurement, a second microprocessor system controlling flowmeter functions and peripheral monitoring devices. An invasive arterial cannula provides continuous measurement of mean arterial pressure (MAP). An electrocardiograph collects the ECG signal and calculates heart rate (HR) (Merlin, Hewlett Packard, USA). The haemodynamic profile integrates ABF, MAP and HR to calculate stroke volume (SV) in the descending aorta (obtained from the formula: \(SVa = ABF/HR\) and total systemic vascular resistance (TSVR) (calculated from the formula: \(TSVRa = (dyne \ s \ cm^2)/MAP\times ABF \times 79.9\)). These two variables are indexed to ABF. Moreover, systolic time intervals (STI) are measured from computerized analysis of the ECG signal (Q wave detection) and the acceleration signal which is derived from the Doppler velocity signal. Opening and closing of the aortic valve are detected by computerized analysis of the acceleration signal. The computer determines the length of the pre-ejection period (PEP) between the Q wave and the beginning of the systolic acceleration front, corresponding to aortic valve opening. Starting at the end of PEP, measurement of the left ventricular ejection time (LVET) is obtained by searching the acceleration signal for the second maximum of systolic deceleration corresponding to aortic valve closure. \(PEPLVET\) and \(LVETI\) are measured automatically and continuously and indexed to HR according to the formula of Weissler, Harris and Schoefeld. The \(PEPLVET\) ratio is also calculated automatically. These values are presented in table form and updated every 8 s on a screen display (fig. 1). Finally, the haemodynamic profile is recorded every 8 s (or at the operator’s request) on soft magnetic support.

MEASUREMENT FOR THE STUDY

When the recorded ABF was satisfactory (stable and clear images of aortic walls and Doppler velocity signal on the screen for more than 1 min), initial data, before skull skin infiltration and skin incision, were
collected simultaneously and served as control values (T1). A second, third and fourth set of haemodynamic measurements were collected using the same criteria, respectively, 3 min after skin incision (T2), 60 min after skin incision (T3) and at the end of the surgical procedure during skin closure (T4). The time T3 was chosen at 60 min after skin incision because preliminary results had shown that at this time blood loss was maximal, with important haemodynamic changes. The oesophageal probe was removed at the end of surgery before discontinuation of anaesthesia.

In an attempt to simplify estimation of blood loss, red cell volumes were used. Estimated body volume (EBV) = 80 ml kg⁻¹ and red cell volume (ERCV) = EBVsPCV were calculated before operation. The following variables were then calculated for the period during operation: estimated red cell volume transfused (RCT) = 0.75×volume of packed red cells; estimated red cell volume deficit (ERCD) = ERCVxPCV variation; estimated red cell volume lost (ERCL) = ERCD + RCT; and percent of ERCV lost = ERCL/ERCV.

Results are reported as mean (SD). Data were compared between T1, T2, T3 and T4 using repeated measures analysis of variance and the Newman–Keuls test. All P values were two-tailed, and P<0.05 was required to reject the null hypothesis. Statistical analysis was performed using NCSS 6.0 software (BMDP Company, Los Angeles, CA, USA).

Results
We studied 12 infants (eight females), treated by the same surgeon; mean age, weight, height and body surface area were 7.0 (range 6–12) months, 7.9 (SD 1.4) kg, 66.7 (3.9) cm and 0.39 (0.06) m², respectively. The nature of the skull deformity was: plagiocephaly in four patients, trigonocephaly in three, scaphocephaly in three and brachycephaly in one. Mean duration of anaesthesia was 236 (37) min, while mean duration of the surgical procedure was 140 (26) min. Total estimated red blood cells lost during the intraoperative period was 158 (77)% of preoperative estimated red cell volume (range 75–213%). ERCV, RCT, ERCD, ERCL and percent of ERCV lost are presented in Table 1.

Mean intraoperative transfusion was 360.0 (169.7) ml (range 180–480 ml) of packed red blood cells.

No untoward incidents were noted using the device. Aortic diameter and ABF measurements were easily obtained in all cases and recording quality was excellent in all patients. However, it was necessary to reposition the oesophageal probe a mean of three times per patient because of loss of the Doppler signal related to displacement of the probe. These displacements were secondary to necessary movements of the head of the infant during the surgical procedure. Table 2 shows the haemodynamic variations during the surgical procedure: ABF, Sa and TSVR were indexed to body surface area (ABFi, SVi, TSVRi). MAP, CVP and ABFi showed parallel changes in individual patients during the procedure (fig. 2).

There was no significant variation in HR, SVi or TSVRi during operation. ABFi, MAP and CVP decreased significantly (P = 0.0475, P < 0.001, P = 0.047, respectively) at the time of maximal blood loss (T3) compared with T1. While CVP and ABFi were not significantly different from control values (T1) at the end of the procedure (T4), MAP remained significantly decreased (P < 0.01). PEPi and PEP/LVET ratio was significantly decreased at the time of skin incision (P < 0.01, P < 0.01, respectively) and increased at the end of the procedure (P < 0.01,

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Mean (SD) blood loss during the study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated red cell volume lost (ml)</td>
<td>281 (119)</td>
</tr>
<tr>
<td>Packed red cell volume transfused (ml)</td>
<td>270 (127)</td>
</tr>
<tr>
<td>% of patient’s estimated red cell volume lost (%)</td>
<td>158 (77)</td>
</tr>
<tr>
<td>Final red cell volume deficit (ml)</td>
<td>11 (8)</td>
</tr>
</tbody>
</table>
Continuous non-invasive ABF measurement in infants

P<0.01, respectively). LVETi was significantly decreased at the end of operation (P=0.015).

**Discussion**

The main result of this preliminary clinical study was that non-invasive aortic blood measurement was feasible during repair of craniosynostosis in children, and estimated complementary haemodynamic trends. The echographic image of the aortic walls and Doppler flow were recorded easily without delay. The haemodynamic data appeared reliable in all cases and similar trends for each infant during surgical repair of craniosynostosis and haemorrhage were obtained: ABFi, MAP and CVP were decreased at the time of maximal blood loss (T3).

The variations in systolic time intervals are a reflection of the inotropic variables: PEP reflects the isometric phase and LVET the isotonic phase of left ventricular contraction. A simplified expression of alterations in systolic time intervals is provided by the ratio PEP/LVET: among normal subjects this ratio averages 0.35±0.04. In adults, increase in PEP/LVET to 0.44 denotes decreased left ventricular performance.20 In contrast, decreases in PEP and PEP/LVET are observed with the use of inotropic drugs. Therefore, the decreases in PEPi and PEP/LVET ratio noted on T2, combined with a non-significant increase in both MAP and ABFi may be related to the positive inotropic effect of epinephrine, used for skull skin infiltration. The increase in PEP/LVET ratio, observed at the end of the surgical procedure, indicated some decrease in left ventricular contractility,21 which was not clinically relevant because ABFi was comparable with control values. This impairment in systolic time interval ratio could be related to metabolic acidosis and hypocalcaemia secondary to the massive blood transfusion. It was of interest to note that despite a significant decrease in MAP, ABFi and CVP at T3, there was no significant increase in TSVRi. This result could be related to the fact that general anaesthesia blunts the circulatory response to haemorrhage.22

Although it has been argued that invasive measurement of cardiac output allows earlier interventions in seriously ill patients or during critical surgical procedures, the practical problems of inserting a pulmonary artery catheter into small children are such that this monitoring device is not used routinely. Thus there is a need in paediatric critical care, and during critical paediatric anaesthesia, for an easy, accurate non-invasive measurement of blood flow.

### Table 2

<table>
<thead>
<tr>
<th>Measurement</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR (beat min⁻¹)</td>
<td>110 (12)</td>
<td>117 (16)</td>
<td>110 (16)</td>
<td>109 (9)</td>
</tr>
<tr>
<td>MAP (mm Hg)</td>
<td>65 (9)</td>
<td>69 (13)</td>
<td>46 (6)</td>
<td>54 (6)</td>
</tr>
<tr>
<td>(60–71)</td>
<td>(60–77)</td>
<td>(42–49)*</td>
<td>(51–57)*</td>
<td></td>
</tr>
<tr>
<td>ABFi (litre min⁻¹ m⁻²)</td>
<td>3.0 (0.8)</td>
<td>3.8 (1.5)</td>
<td>2.0 (0.8)</td>
<td>3.1 (1.6)</td>
</tr>
<tr>
<td>(2.5–3.5)</td>
<td>(2.7–4.8)</td>
<td>(1.5–2.5)*</td>
<td>(2.0–4.2)</td>
<td></td>
</tr>
<tr>
<td>PEPi (ms)</td>
<td>131 (20)</td>
<td>112 (17)</td>
<td>136 (8)</td>
<td>148 (10)</td>
</tr>
<tr>
<td>(118–144)</td>
<td>(99–123)*</td>
<td>(130–141)</td>
<td>(142–155)*</td>
<td></td>
</tr>
<tr>
<td>LVETi (ms)</td>
<td>467 (23)</td>
<td>468 (21)</td>
<td>462 (29)</td>
<td>437 (21)</td>
</tr>
<tr>
<td>PEP/LVET</td>
<td>0.30 (0.06)</td>
<td>0.25 (0.05*)</td>
<td>0.31 (0.04)</td>
<td>0.36 (0.04)</td>
</tr>
<tr>
<td>(0.26–0.34)</td>
<td>(0.21–0.28)</td>
<td>(0.29–0.34)</td>
<td>(0.33–0.39)*</td>
<td></td>
</tr>
<tr>
<td>SVi (ml m⁻²)</td>
<td>29 (8)</td>
<td>33 (13)</td>
<td>25 (19)</td>
<td>31 (15)</td>
</tr>
<tr>
<td>(24–33)</td>
<td>(25–42)</td>
<td>(13–38)</td>
<td>(21–42)</td>
<td></td>
</tr>
<tr>
<td>TSVRi (dyn s cm⁻¹ m⁻²)</td>
<td>2003 (822)</td>
<td>1998 (1315)</td>
<td>2269 (1454)</td>
<td>2352 (1533)</td>
</tr>
<tr>
<td>(1481–2526)</td>
<td>(1114–2882)</td>
<td>(1314–3193)</td>
<td>(1322–3382)</td>
<td></td>
</tr>
<tr>
<td>CVP (mm Hg)</td>
<td>5 (2) (4–7)</td>
<td>5 (2) (4–7)</td>
<td>3 (2*) (2–4)</td>
<td>6 (3) (4–7)</td>
</tr>
</tbody>
</table>

*P<0.05 vs T1

**Figure 2** Evolution of MAP, CVP and ABFi in individual patients. MAP, CVP and ABFi showed parallel changes in individual patients. The same symbols are used for the same patients in the three figures.
Blood flow measurement using ultrasound techniques represents a suitable approach during general anaesthesia\(^1\) and has acceptable agreement and precision compared with the direct Fick method. In fact, this non-invasive method has been shown previously to correlate well with electromagnetic flow in animals\(^2\) and with thermodilution in humans.\(^3\)\(^-\)\(^14\) The device allows measurement of aortic diameter and velocity at the same anatomical level continuously and non-invasively. The importance of this simultaneous measurement has been outlined previously in adults\(^16\) and in children.\(^17\) Moreover, aortic diameter is probably the most important single determinant of infants and children.\(^18\) Studies are needed to evaluate how this new monitor-complementary haemodynamic trends during a cardiac cycle\(^3\)\(^1\)\(^2\) and with pressure, the relationship being almost linear.\(^3\)\(^1\)\(^2\) For the purpose of our study we used a device which is the only one available enabling simultaneous measurement of aortic diameter and velocity. Until recently, this monitoring technique was not available in infants, however the recent development of a miniaturized probe has remedied this. Gueugniaud and colleagues have demonstrated the feasibility of this device in infants and have shown some myocardial depression from isoflurane.\(^3\)\(^5\) However, contrary to our study, MAP was not measured continuously, which may have influenced the results, especially regarding the calculation of TSVRa (MAP/ABFx79.9).

In summary, our results have confirmed the feasibility of this device and that it may provide non-invasive, complementary haemodynamic trends during a haemorrhagic surgical procedure in infants. Further studies are needed to evaluate how this new monitoring device may influence the perioperative management of infants and children.

### Acknowledgements
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### References
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