Cerebral effects of aortic clamping during coarctation repair in children
A transcranial Doppler study

Rosendo A. Rodriguez a,*, Nihal Weerasena a, Garry Cornel a, William M. Splinter b, David J. Roberts b

a Division of Cardiovascular Surgery, Department of Surgery, Children’s Hospital of Eastern Ontario, 401 Smyth, Ottawa, Ontario, K1H 8L1, Canada
b Department of Anaesthesia, Children’s Hospital of Eastern Ontario, 401 Smyth, Ottawa, Ontario, K1H 8L1, Canada

Received 29 September 1997; accepted 16 December 1997

Abstract

Objective: Haemodynamic changes as a consequence of application and release of aortic clamps for surgical repair of aortic coarctation are compensated by cerebrovascular autoregulation. Transcranial Doppler was used to study the effect of these haemodynamic changes upon brain circulation in children during aortic coarctation repair. Method: A 2-MHz transcranial Doppler system continuously recorded mean cerebral blood flow velocities from the left middle cerebral artery in 13 children (aged from 5 days to 14 years) during repair of their coarctation. Measurements were performed: prior to aortic clamping (baseline); during the first 5 min after clamp application; 1 min before declamping; at 1, 2, 4 and 6 min after the release of both proximal and distal aortic clamps; and at initial chest closure. A contralateral upper-limb non-invasive blood pressure cuff measured systemic blood pressures. Haemodynamic and anaesthetic parameters were monitored. Patients were stratified by age into two groups: age < 6 months (group A) and age ≥ 6 months (group B). Results: With aortic clamping, systemic blood pressures (range from: 16 to 54%) and cerebral blood flow velocities (range from: 40 to 19%) changed slightly (P < 0.05) from initiation to end of aortic clamping. In group A, release of aortic clamps resulted in moderate fluctuations in systemic blood pressures (range from: 34 to 15%) (P < 0.05) and a marked reduction in cerebral blood flow velocities (range from: 63 to 33%) (P < 0.01). At the time of surgical closure, flow velocities had improved in all infants except one. Group B did not show major reductions in either cerebral blood flow velocity or systemic blood pressures throughout all measurements (P > 0.05). During aortic clamp release, young infants responded with lower brain blood flow velocities as compared to older children (r = 0.68; P < 0.05). Conclusion: Transient central nervous system hypotension results as a consequence of flow redistribution during aortic declamping in young infants. Older children usually show a faster autoregulatory compensation to these haemodynamic changes. The observed age-related physiologic differences, suggest that young infants may require higher systemic blood pressures during declamping to prevent the cerebral blood flow reduction. Transcranial Doppler appears to be a valuable monitor of these cerebral haemodynamic changes. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Cerebral autoregulation; Transcranial Doppler; Brain circulation; Children

1. Introduction

During cardiac surgery in children, adequate cerebral perfusion is necessary for the prevention of brain ischaemia. Transient hypotension, may occur during this type of surgery and may be compensated for by cere-
Transcranial Doppler technique [1]. However, neonates or critically ill infants have defective cerebral autoregulation which leads to decreased cerebral circulation after reduction in cerebral perfusion pressure [2,3].

Transcranial Doppler ultrasonography is a non-invasive monitor that measures blood flow velocities in the basal intracranial arteries [4,5]. Since changes in the arterial diameter are thought to be minimal (less than 4%) during normothermic conditions [5–7], the relative variations in the flow velocity pattern have been correlated with changes in regional cerebral blood flow, as demonstrated by invasive methods [4,8,9]. Since transcranial Doppler offers an adequate temporal resolution for flow velocity measurements, this technique has been used to investigate cerebrovascular autoregulation [8,10,11].

Surgical repair of coarctation of the aorta requires clamping of the distal aortic arch in close proximity to the head and neck vessels. The application and release of the clamps may potentially affect cerebral circulation [12]. If the collateral circulation to the brain is inadequate, a partial occlusion of the brain-supplying neck vessels during clamping may decrease effective cerebral perfusion. In contrast, sudden release of the proximal and distal aortic clamps may result in a transient state of hypotension during reperfusion of the lower limbs [1,11,13].

The purpose of our study was to use transcranial Doppler to evaluate the haemodynamic effects of aortic clamping and declamping on cerebral circulation during surgical repair of aortic coarctation in children.

2. Material and methods

2.1. Population sample

As part of our intraoperative neuromonitoring protocol for pediatric cardiac surgery and following informed consent for the operation, 13 children (aged from 5 days to 14 years) were studied during surgical repair of aortic coarctation.

2.2. Transcranial Doppler technique

Prior to surgical incision, a 2-MHz pulsatile-wave Doppler probe (Medasonics, Fremont CA) was applied to the left temporal window. The signal was range-gated to a depth sufficient to consistently insonate the left middle cerebral artery. After the optimum signal was achieved, the probe was secured.

A transcranial Doppler system (Neuroguard Plus™, Nicolet, Madison, WI) continuously calculated the averaged mean flow velocities from the last five cardiac cycles. Under stable anaesthetic conditions, cerebral blood flow velocities were measured: prior to proximal aortic clamping (measurement 1, baseline), during the first 5 min after aortic clamping (measurement 2), 1 min before proximal declamping (measurement 3), at 1, 2, 4 and 6 min after the release of both proximal and distal aortic clamps (measurements 4–7), and finally, at initial surgical chest closure (measurement 8).

2.3. Anaesthetic monitoring

A contralateral upper-limb non-invasive blood pressure cuff measured systemic blood pressures every 3 min during standard monitoring or as frequent as every min during critical periods. The end-tidal CO2, inspired fraction of oxygen, transcutaneous arterial oxygen saturations, nasopharyngeal temperature, and heart rate were also continuously monitored.

2.4. Anaesthetic management

If required, premedication consisted of midazolam administered orally. Induction of anaesthesia was accomplished intravenously by sufentanil (0.5 μg/kg) or fentanyl (2.5 μg/kg) and supplemented with a volatile agent. Anaesthesia was maintained with sufentanil (0.2 μg/kg per h) or fentanyl (5–10 μg/kg) and isoflurane (0.2–2.4% end-tidal). Increases in systemic blood pressure during aortic clamping were controlled by titrating isoflurane in a dose/response fashion. Muscle relaxants were used as required.

2.5. Clinical evolution

Although no formal neurologic examination was performed, patients were followed during their stay in the intensive care unit looking for presence of seizures or motor abnormalities according to our postoperative follow-up protocol.

2.6. Data analyses

In order to decrease inter-subject variability, measurements of cerebral blood flow velocities were expressed as a percentage relative to the preclamping baseline. Since age may affect the brain autoregulatory response to these surgical maneuvers, and because the age-related effects upon cerebral blood flow velocities are greater within the first 6 months of life [5], patients were stratified by age into two groups as follows: group A, included patients below 180 days, and group B, patients equal to or above 180 days.

2.7. Statistical methods

Data were tested for normalcy and logarithmic transformation was used to fit requirements for parametric analyses. Data in figures are expressed as the mean ±
3. Results

3.1. Cerebral haemodynamics

In group A, mean systemic blood pressures (range from $-16$ to $+54\%$) and cerebral blood flow velocities (range from $-40$ to $+19\%$) during aortic clamping slightly changed ($P > 0.05$) from initiation to end of clamping (measurement 3). The release of the aortic clamps in this group (measurement 4), resulted in marked reductions (range from $-63$ to $-33\%$) in cerebral blood flow velocities ($P < 0.01$) and moderate changes (range from $-34$ to $+15\%$) in mean systemic blood pressures ($P > 0.05$) as compared to preclamping values (Fig. 1). These two haemodynamic parameters gradually improved within the next 2 min (measurements 5 and 6) and returned near preclamping values during chest closure. At this measurement, most patients showed reduction in flow velocities less than 30% from baseline, except for one case whose flow velocities and mean systemic blood pressures decreased by 39 and 22%, respectively.

In contrast, older children (group B) had a different cerebral haemodynamic response. In this group, increases in systemic pressures (range from $+7$ to $47\%$) and use of high isoflurane concentrations (range from
0.5 to 2.5% end-tidal) \( (P > 0.05) \) during the clamping period (measurements 2 and 3) did not alter cerebral blood flow velocities \( (P > 0.05) \). Prior to declamping, large variations in blood flow velocity (range from \(-45\) to \(+86\)% and systemic pressures (range from \(-14\) to \(+54\)% were observed in this group of patients. Subsequently, aortic declamping caused a brief period (<15 s) of a mild, transient reduction in cerebral blood flow velocities. Flow velocities immediately returned to values greater than 70% from baseline within the next 20 s remaining stable throughout the rest of the case \( (P > 0.05) \).

The variations in cerebral blood flow velocity during aortic clamp release and age were significantly correlated \( (r = 0.68; P < 0.05) \). Younger children responded with lower flow velocities during declamping (measurement 4) as compared to older children \( (P = 0.01) \). No correlation was demonstrated between flow velocity changes at this measurement and systemic blood pressure, end-tidal CO\(_2\), weight, cross clamping time, or isoflurane concentrations.

End-tidal CO\(_2\) and isoflurane management were maintained at constant levels throughout all measurements in both groups of patients \( (P > 0.05) \). Younger children usually required lower end-tidal isoflurane concentrations compared to older patients during aortic clamping \( (P < 0.05) \). Although higher isoflurane concentrations were used in patients of group B (Fig. 2), differences in volatile concentrations compared to preclamping values were non-significant \( (P > 0.05) \). In addition, temperature, end-tidal CO\(_2\), transcutaneous oxygen saturations and hematocrit management were similar in these two groups \( (P > 0.05) \), and only heart rates were significantly higher in the younger group \( (P < 0.05) \).

### 3.2. Clinical evolution

There were 11 patients discharged from hospital without apparent neurologic complications, one patient had seizures associated with intraventricular hemorrhage that required management. Only one patient died 4 days after surgery due to presence of sepsis, coagulopathy and renal insufficiency.

### 4. Discussion

#### 4.1. Flow velocities

Our results indicate that the application and release of the aortic clamp during surgical repair of coarctation
of the aorta affects cerebral haemodynamics of young infants. In this age group, moderate reductions in systemic blood pressures with declamping were followed by prolonged periods of severe reduction in cerebral blood flow velocity as determined by transcranial Doppler. In contrast, these haemodynamic effects were shorter and less severe in older children, which suggests a more efficient autoregulation in this age group. In addition, the association between flow velocity changes and age at declamping, indicates that these haemodynamic changes exceed the lower limit of cerebral autoregulation in young infants [1–3,5].

During the period of aortic clamping, systemic blood pressures and cerebral blood flow velocities changed slightly in both groups of patients. In spite of fluctuations in flow velocity, some older patients showed moderate reductions in blood flow velocities prior to declamping. This effect may be associated to anaesthetic maintenance, as older children usually required higher end-tidal isoflurane concentrations because of increases in systemic blood pressure at initial clamping. The cerebral vasodilatation produced by isoflurane [13] may have been outweighed by the effective reduction in systemic blood pressures due to the stepwise increases in isoflurane concentration. Although decreases in cerebrovascular resistance and metabolic depression has been demonstrated during high isoflurane anaesthesia in animal models [13,14], its effects on cerebral blood flow velocities particularly in children are less clear. While in this investigation, we did not intend to evaluate the effects of isoflurane on cerebral blood flow velocity, previous studies [15] have demonstrated that in healthy anaesthetized children, controlled increases in isoflurane concentration have resulted in no changes in flow velocities.

4.2 Cerebral autoregulation

Following aortic declamping, reperfusion of the lower part of the body usually results in transient systemic hypotension [1,13,16]. As a consequence, variations in cerebral perfusion pressure are expected, but these changes are tempered by cerebrovascular autoregulation [1–3,8,9,11,13]. However, when variations in cerebral perfusion pressure exceed the limits of this autoregulatory response, cerebral blood flow changes in parallel with alterations in cerebral perfusion pressure [13]. The integrity of cerebral autoregulation in children is considered to be important in preventing brain injury [2,3]. Aaslid et al [10,11] described a method to evaluate dynamic cerebral autoregulation in humans using transcranial Doppler during rapid changes in systemic blood pressure induced by the rapid deflation of thigh blood pressure cuffs. The haemodynamic changes observed in our two groups of children during blood flow redistribution consecutive to aortic declamping are similar. Our results suggest that haemodynamic changes are usually compensated within the next 120 s in young infants and in only 20 s in older children. Several studies suggest that following a disturbance in cerebral perfusion pressure, a steady state flow to the brain is accomplished within 1 min in some animal species [17–19], but in adult humans adequate compensation is expected in less than 1 min [11,13,16]. Thus, our results suggest that children older than 6 months autoregulate similar to adults.

Although little is known regarding cerebral autoregulation in anaesthetized children, previous investigations in adults [1,13,20] suggest that the lower limit of cerebral autoregulation in non-anaesthetized patients occurs when systemic blood pressures decrease by approximately 25% below the resting value. In addition, it appears that anaesthetics agents with a direct cerebral vasodilating properties decrease the effective lower limit of cerebrovascular autoregulation [20]. The results of the present investigation in children, whose anaesthesia was supplemented with isoflurane suggest that reductions in systemic blood pressures of approximately 20% from baseline at declamping, resulted in a completely different cerebral haemodynamic response between the two groups. It was evident from this study, that the effects on flow velocities elicited by changes in systemic pressure lasted longer in young infants, while any contribution to this effect produced by the end-tidal CO₂, hematocrit or isoflurane management was considered to be minimal.

4.3 Transcranial Doppler

Blood flow velocities in major cerebral arteries can now be measured by the Doppler technique [4,5]. Cerebrovascular autoregulation can be evaluated by following cerebral blood flow velocities during stepwise alterations in systemic blood pressure [8,11,16]. Since the relative variations in flow velocities have been correlated with changes in regional cerebral blood flow [8,9], transcranial Doppler can provide instantaneous information regarding status of cerebral autoregulation [1,10,11,16].

4.4 Clinical implications

Knowledge of the physiology of cerebrovascular autoregulation in children is essential for their optimal medical management. The marked reduction in blood flow velocities was associated with moderate changes in systemic blood pressures in young infants. Thus, young infants may be at increased risk of cerebral adverse events during marked reductions in systemic blood pressures. Surgical and anaesthetic techniques that minimize blood pressure changes during manipulation and release of aortic clamps may be desirable in infants.
In conclusion, the physiologic consequences of flow redistribution upon brain circulation during repair of aortic coarctation were studied by transcranial Doppler. Although a small percentage of clinical complications were detected in this group of patients, further studies are necessary to investigate the clinical relevance of these hemodynamic changes. Nevertheless, the application of transcranial Doppler to the study of brain circulation during surgery, may provide some insight into the potential effects of our surgical manipulations and on the efficiency of the autoregulatory response in small children.

Acknowledgements

Dr. Rosendo A. Rodriguez was a recipient of the Popham Clinical Research Fellowship Award by the Children’s Hospital of Eastern Ontario Foundation. The authors appreciate the cooperation of the cardiac staff of the Department of Anaesthesia, residents of the Division of Cardiovascular Surgery and nurses. The assistance of Carlos Daniel and David Rodriguez during data analyses is gratefully appreciated.

References


Appendix A. Conference discussion

Dr R.A. Neiroti (Grand Rapids, Michigan, USA). Usually when you apply the aortic clamp, there is an increase in the proximal pressure. Have you used any vasodilator to treat that in these patients which might have affected your results?

Dr Weerasena: Yes. We always used an inhalation anaesthetic to control the blood pressure during that time. And there was no relationship to the amount we used before and after to control the pressures. After we achieved this, the concentration of the anaesthetic agent was steady throughout.