Cerebral regional oxygenation during aortic coarctation repair in pediatric population

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Abstract

Objective: During repair of aortic coarctation, clamping of the transverse aortic arch proximal to the left common carotid artery occludes blood flow to the left carotid and vertebral arteries. The objective of the present study is to determine whether blood flow through the right carotid and vertebral arteries provides adequate cerebral blood flow during aortic cross-clamping, as assessed by near-infrared spectroscopy.

Methods: In 11 consecutive children undergoing aortic coarctation repair through a standard posterolateral thoracotomy, regional cerebral oxygen saturation (cSO2) was measured using near-infrared spectroscopy. Six patients underwent an extended end-to-end repair, in which the aortic cross-clamp was placed in between the innominate and left common carotid arteries (extended repair group). Five patients underwent a standard end-to-end repair in which the cross-clamp was clamp placed between the left common carotid and subclavian arteries (standard repair group).

Results: After aortic clamping, there was a significant decrease in cSO2 in the extended repair group, whereas the cSO2 decreased linearly during the aortic cross-clamping period (\( r = -0.842, p < 0.001 \)). Regression analysis identified the site of aortic cross-clamping as the sole independently significant variable explaining changes in the cSO2 during aortic cross-clamping ( \( p < 0.03 \) ), whereas neither age nor duration of aortic cross-clamping was statistically significant. There were no postoperative neurological impairments in either group of patients.

Conclusion: During aortic coarctation repair, aortic cross-clamping proximal, as compared to distal, to the left carotid artery is associated with significantly decreased regional cerebral oxygen saturation, as measured by near-infrared spectroscopy. Although no short-term clinical impairments were identified, long-term follow-up in a larger cohort is needed to study the effects of unbalanced cerebral oxygenation during clamping of the transverse arch. These data suggest that cerebral saturation monitoring is warranted, and may be indicative of cerebral hypoperfusion.

Keywords: Aortic coarctation; Cerebral protection; Near-infrared spectroscopy

1. Introduction

Neurological complications after pediatric cardiac surgery remains an ongoing concern, with a reported incidence of 2.3% for overt clinical presentation [1], and between 54% and 67% when magnetic resonance imaging is used [2, 3]. Aortic arch procedures commonly rely on the right brachiocephalic and common carotid arteries for cerebral perfusion, the assumption being that collateral blood flow and completeness of the circle of Willis allow for a more or less even distribution of blood flow to the two hemispheres. However, incompleteness of the circle of Willis is far more commonly the case, with only 21% of the general population reported to have a complete circle of Willis [4].

The purpose of this study was to assess cerebral regional oxygen saturation (cSO2) using near-infrared spectroscopy during aortic coarctation repair, and compare the effects of placing the aortic cross-clamp either before or after the takeoff of the left common carotid artery. We tested the hypothesis that there was no difference in cerebral oxygen saturation based on where the aortic cross-clamp is placed, making the assumption that the right common carotid and circle of Willis would provide adequate bihemispheric cerebral perfusion.
2. Materials and methods

Institutional review board approval from Case University Medical Center was obtained, and the requirement for informed consent was waived as near-infrared spectroscopy is a routine monitoring procedure used during cardiac surgery at our center. This is a retrospective observational study of patients undergoing isolated repair of aortic coarctation through a posterolateral thoracotomy incision without the use of cardiopulmonary bypass. Patients who had other concomitant procedures were excluded from the study. Study patients were divided in two groups according to the site of aortic cross-clamping, either proximal to the left carotid artery during an extended end-to-end repair, or distal to the left carotid artery during a standard end-to-end repair.

Hospital, operative, and clinic records were obtained, including pre- and postoperative echocardiographic and cardiac catheterization data. Variables selected for statistical analysis included demographic variables, type of cardiac anomaly, duration of aortic cross-clamping, regional cerebral and somatic oxygen saturation, length of hospital stay, and perioperative morbidity and mortality.

2.1. Surgical approach

The aortic arch, arch branches, patent arterial duct, intercostal vessels and descending aorta were dissected and widely mobilized. The arterial duct was doubly ligated and divided. In patients undergoing an extended end-to-end anastomosis, proximal control was obtained by clamping the aorta between the innominate and left carotid arteries. Conversely, in those undergoing a standard repair, proximal control was obtained by clamping the aorta in between the left carotid and left subclavian arteries. The aorta was opened and the coarctation segment excised. The undersurface of the aortic arch was opened to the proximal clamp, and an end-to-end anastomosis between the divided distal end of the descending aorta and undersurface of the aortic arch was constructed using absorbable suture. The anastomosis was deaired and the clamps removed off the intercostal arteries, distal aorta, and proximal aorta in that sequence.

2.2. Near-infrared spectroscopy

Cerebral oxygenation was monitored using the INVOS cerebral oximeter (INVOS 5100; Somanetics Corp., Troy, MI). This technique uses near-infrared light to measure the absorption spectra of the total hemoglobin and deoxyhemoglobin in the frontal cerebral cortex [5]. One light-emitting diode and two detectors, adjusted 3 and 4 cm from the light-emitting diode, are used. The 3 cm detector mainly measures light passing within the shallow structures of the skull, skin, and soft tissues. The 4 cm detector measures light passing through both the shallow structures and deeper tissues within the frontal cortex. A subtraction algorithm is used to correct for the signal from the extracranial tissues, and a percentage of regional oxygen saturation is obtained, one that is derived as the percentage of the oxyhemoglobin to the total hemoglobin [6].

The near-infrared spectrophotometer used at the time of this study was equipped with two monitoring channels. One was placed across the middle of the forehead below the hairline, measuring oxygen saturation of both cerebral hemispheres (cSO2), while the other was placed on the right flank near the kidney, thereby measuring regional oxygen saturation of the somatic circulation (sSO2).

Cerebral and somatic saturations as measured by near-infrared spectroscopy were recorded at 30 s intervals during the entire operative procedure. The collected data were divided into three periods, namely from just after induction of anesthesia to aortic cross-clamping, during the aortic cross-clamping period, and for at least 15 min after removal of the aortic cross-clamp.

2.3. Data analysis

Data were collected and statistically analyzed using Sigma Stat 3.5 software (Systat Software Inc., Point Richmond, CA, USA). Data obtained from near-infrared spectroscopy were converted into percent of change from baseline, where the baseline was defined as the mean saturation before aortic cross-clamping, and reported as mean ± standard deviation. Student’s t-test analysis was used to compare continuous data while the Mann–Whitney U-test was used to compare ordinal and non-normally distributed data. Nominal data were compared using Fisher’s exact test. Paired t-test analysis was used to compare regional oxygen saturation before, during and after cross-clamping. Spearman’s rank correlation (r_s) was used to assess the relationship between cSO2 and aortic cross-clamping time. Simple and multiple regression analysis was used to assess the relationship between changes in cSO2 with patient age, weight, sex, coarctation type, aortic cross-clamp time, and type of surgical procedure. A p value <0.05 was considered to be statistically significant.

As this was an observational secondary analysis, a power calculation was not performed in advance. Nevertheless, a sample size of 11 patients proved sufficiently large to detect a relative change of 20% from the baseline cSO2, assuming a standard deviation of 15%, with a power of 82%, and an alpha of 0.05. We chose a 20% change of cSO2 from baseline based on previously performed studies that demonstrated a more frequent incidence of acute neurological changes with this level of cerebral desaturation [7,8].

3. Results

3.1. Patient characteristics

Eleven consecutive patients, undergoing isolated aortic coarctation repair by a single surgeon, met the inclusion criteria, and were included in the study population. The mean age at operation was 16.4 ± 31.1 months (range of 8 days–8 years, median of 1.2 months), with a mean weight of 6.8 ± 7.3 kg (range of 1.7–23 kg, median of 3.6 kg). There were five male and six female patients, and concomitant cardiac defects included ventricular septal defect in five, and bicuspid aortic valve in five.

Six patients had an extended end-to-end repair with the aortic cross-clamp placed proximal to the left common carotid artery (extended repair group), whereas five patients...
underwent a standard end-to-end anastomosis with the clamp placed distal to the left common carotid artery (standard repair group). There were no statistically significant differences between the two groups, except for weight, which was higher in patients undergoing a standard end-to-end repair (11.9 ± 8.8 vs 2.8 ± 0.9 kg, \( p = 0.03 \), Mann–Whitney test). The mean aortic cross-clamp time was 20.4 ± 7.8 min (range of 11–34 min), and did not differ significantly between the two groups.

3.2. Regional cerebral oxygen saturation

After aortic cross-clamping, there was a decrease in cSO\(_2\) in the extended repair group, but an increase in cSO\(_2\) in the standard repair group (−9.2 ± 12.2% vs +6.0 ± 5.1%, \( p = 0.03 \), Mann–Whitney test, Fig. 1). In the extended repair group, the cSO\(_2\) showed an inverse linear relationship over time during aortic cross-clamping (\( r_S = -0.842, \ p < 0.001, \) Spearman’s rank correlation, Fig. 2), while in patients undergoing a standard repair, there was a positive linear relationship (\( r_S = 0.786, \ p < 0.001, \) Spearman’s rank correlation, Fig. 3).

In the extended repair group, there was a decrease in the cSO\(_2\) during aortic cross-clamping (mean decrease of 9.2 ± 12.2%, \( p = 0.12, \) paired \( t \)-test), which increased after the clamp was removed (mean increase of 13.9 ± 15.7%, \( p = 0.08, \) paired \( t \)-test, Fig. 4). Conversely, in the standard repair group, there was a relative increase in cSO\(_2\) during aortic cross-clamping (mean increase of 6.0 ± 5.1%, \( p = 0.05, \) paired \( t \)-test), which was followed by decrease towards baseline after removal of the clamp (mean decrease of 5.6 ± 3.2%, \( p = 0.02, \) paired \( t \)-test, Fig. 5). Linear regression analysis identified the site of aortic clamping as the sole independent variable accounting for changes in cSO\(_2\) (\( p = 0.03 \)). Significantly, age at operation and duration of aortic cross-clamping were not statistically significant.
The cerebral somatic oxygenation increased with aortic cross-clamping, and returned to baseline after application and removal of the aortic cross-clamp in the standard repair group. The cSO2 increased with aortic cross-clamping, and returned to baseline levels after removal of the cross-clamp.

3.3. Regional somatic oxygen saturation

The regional somatic oxygen saturation decreased in both groups with aortic cross-clamping, and there was no significant difference between groups ($p = 0.6$, t-test).

3.4. Early postoperative period

Patients undergoing an extended end-to-end repair had a longer hospital stay as compared with those who had a standard repair (9.5 ± 7.8 vs 3.4 ± 0.5 days, extended vs standard repair groups respectively, $p = 0.05$, Mann–Whitney test). At a mean follow-up of 12 ± 1.3 months, there have been no neurological impairments detected in either group, and no mortality, recoarctation, or other comorbidities.

4. Discussion

Isolated aortic coarctation repair is usually associated with low morbidity and favorable results [9]. Neurodevelopmental outcomes have not been exhaustively studied in this group of patients, even in larger studies looking at neonates undergoing aortic coarctation repair [10,11]. As a group, when assessed later in life, neonates with congenital heart disease perform within population norms [11], whereas children with congenital heart disease perform consistently below reference populations [11,12].

Aortic coarctation repair, with or without arch hypoplasia, necessitates wide mobilization of arch vessels, the descending aorta, and intercostal arteries. Ductal tissue is excised, and a large tension-free anastomosis to the undersurface of the aorta is thought to reduce the incidence of recoarctation. The operative procedure requires control of the arch either proximal or distal to the left carotid artery. In patients in whom control is gained proximal to the left common carotid artery, the assumption is made that collateral blood flow and the circle of Willis will allow for a more or less even distribution of cerebral blood flow to both hemispheres. However, variation in the circle of Willis is common, and only 21% of the general population have a complete circle of Willis [4]. Magnetic resonance angiography demonstrates an incomplete (anterior and posterior) circle of Willis in 6% of healthy young adults [13], while color Doppler patterns are abnormal in 10% of full-term neonatal patients [14].

Near-infrared spectroscopy has emerged as the noninvasive method of choice to monitor changes in tissue chromophore concentration [15,16], and correlates well with cerebral blood flow [17], oxygenation [15], and cellular energetics [18]. Previous reports have demonstrated the importance of bitemporal near-infrared spectroscopy monitoring in adult patients when cerebral perfusion is based on one carotid artery. In 100 patients undergoing carotid endarterectomy with regional anesthesia, Samra and colleagues [8] reported that patients with neurological symptoms showed a greater decline of cSO2 during carotid occlusion. Janelle and associates [19] reported a case of bilateral near-infrared spectroscopy monitoring during emergency repair of a DeBakey type I aortic dissection. A rapid decrease in right cSO2 from 65% to <20% accurately detected the dissection extending to the right common carotid artery, allowing for a rapid change in mechanical perfusion strategy.

Rodriguez and associates [20] reported on cerebral perfusion during aortic coarctation repair in children using transcranial Doppler scanning to monitor middle cerebral artery blood velocity. The authors found transient central nervous system hypoperfusion as a consequence of flow redistribution during aortic declamping in young infants, whereas older children usually showed faster autoregulatory compensation to the hemodynamic changes after unclamping the aorta. In a study of 18 children undergoing aortic coarctation repair with bilateral near-infrared spectroscopy monitoring, Azakie and his colleagues [21] noticed a significant decrease in hemoglobin difference levels, a surrogate marker of cerebral blood flow, and significant impairment in cerebral oxygen balance of the left hemisphere with proximal clamping of the aortic arch. This was associated with an increase in oxygen balance and hemoglobin difference proximal to the clamp.

In the present study, proximal occlusion of the aortic arch resulted in a significant decrease in cerebral oxygen saturation that continued to decline throughout the clamping period, a change that was statistically significant ($r_S = -0.842$, $p < 0.001$, Fig. 2). This strongly implies an increasing risk to neurological injury with the passage of time in patients in whom the clamp is placed proximal to the left common carotid artery. This effect is not present in patients in whom the clamp is placed distal to the left common carotid artery. There was no clinical postoperative neurological impairment in either group at a mean follow-up of 12 ± 1.3 months. The absence of neurological impairment might be due to the fact that the decrease in the cSO2 during the period of aortic cross-clamping in the extended repair group was only 9.2 ± 12.2% from baseline, while other clinical studies demonstrated a more frequent incidence of acute neurological changes with a relative change of 20% from baseline cSO2 [7,8].

This data emphasizes the importance of bilateral monitoring of cerebral oxygenation during aortic coarctation repair, as well as for aortic arch reconstruction using selective antegrade cerebral perfusion. Several methods
may increase a low s\textsubscript{O2} while on cardiopulmonary bypass. These include increasing the bypass flow rate, increasing PaCO\textsubscript{2}, hemoglobin concentration, and decreasing core temperature [7]. Andropoulos and his colleagues reported that a high flow protocol, composed of pH-stat management and receptor blockade, yielding selective antegrade cerebral perfusion flow rates of 64 ml/kg/min, would offer higher left sided s\textsubscript{O2} as compared to low flow protocols [22,23]. Nevertheless, sustained differences in cerebral oxygen saturation remained, with the left side always lower than the right [22].

A number of measures can be adopted to minimize the risk of left cerebral hemisphere oxygen desaturation: This incorporates intraoperative bilateral cerebral monitoring using non-invasive tools as near-infrared spectroscopy or transcranial Doppler. Avoid afterload reduction for management of right radial arterial hypertension during aortic clamping. Hypotension during aortic cross-clamping may disrupt cerebral autoregulatory mechanisms, and lead to significant impairment in cerebral oxygen balance [21]. Slight persistent compression on the descending aorta after removing the clamp have been reported to decrease the hypotension, flow redistribution and reduction in cerebral blood flow occurring during that phase of repair [20]. A transternal approach with hypothermic selective antegrade cerebral perfusion might provide better cerebral protection especially in cases involving aortic arch hypoplasia. Preoperative and postoperative magnetic resonance imaging can be done to interpret the significance of transient decrease in cerebral saturation during repair and provide a mean of follow-up together with neurological development.

The present study is limited in being a retrospective analysis of a small cohort of patients. Because of technical limitations of the currently available near-infrared spectroscopy equipment in this physically small group of patients, right versus left hemispheric oxygen saturation could not be obtained. Newer technologies will shed further light on this subject in the future.

We conclude that the site of clamp placement during aortic coarctation repair makes a significant impact on oxygen saturation as measured by near-infrared spectroscopy. Patients in whom the clamp is placed proximal to the left common carotid artery have a progressively declining cerebral saturation during the aortic cross-clamping period, which is in stark contrast to the increase in cerebral saturation seen in patients in whom the clamp is placed distal to the left common carotid artery. Further study is needed to clarify whether these changes result in different clinical outcomes (none were observed in this study), and whether left versus right cerebral saturation monitoring will shed any further light on this important matter.

References


[22] Andropoulos DB, Diaz LK, Fraser Jr CD, McKenzie ED, Stayer SA. Is bilateral cerebral perfusion might provide better cerebral protection especially in cases involving aortic arch hypoplasia. Preoperative and postoperative magnetic resonance imaging can be done to interpret the significance of transient decrease in cerebral saturation during repair and provide a mean of follow-up together with neurological development.

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References


hemisphere. Does that mean that you may also create potential ischemia in the spinal cord circulation?

**Dr Farouk:** Actually, what we were more focused on, during the course of this study, was the changes in cerebral oxygenation with respect to the site of aortic clamping. Regarding the spinal cord ischemia, we didn’t have any cases with neurological insult in the current series. However, I can’t really judge whether the change in the site of aortic clamping would really affect the oxygenation level in the spine cord or not.

**Dr Tsang:** The rationale of a successful, safe coarctation repair is collateral support from the subclavians.

**Dr Farouk:** I completely agree with you, but as I said, we don’t have enough data at the time being to comment on this issue.