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Jugular bulb desaturation during off-pump coronary artery bypass surgery

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Abstract
Purpose. Off-pump coronary artery bypass grafting surgery (OPCAB) frequently results in significant jugular bulb desaturation. Although jugular bulb desaturation during OPCAB may be associated with postoperative cerebral injury, routine jugular bulb oximetry appears to be invasive and expensive. We hypothesized that intraoperative hemodynamic compromise during OPCAB due to cardiac displacement is associated with jugular bulb desaturation which correlates with specific hemodynamic and physiological changes.
Methods. Hemodynamic and physiological data were measured at the following points: (1) before anastomosis of the coronary artery (baseline); (2) during anastomosis of the left anterior descending artery; (3) during anastomosis of the circumflex branch or posterior descending artery; and (4) after chest closure. Arterial, mixed venous, and jugular venous bulb blood gas analyses were performed serially.
Results. Jugular bulb desaturation (≤50%) frequently occurred during surgical displacement of the heart. Mixed venous oxygen saturation (Sv_{O_2}), partial pressure of carbon dioxide (Pa_{CO_2}), and central venous pressure (CVP) showed a significant relationship with jugular bulb oxygen saturation ($r = 0.45$) by multivariate linear regression analysis. Multivariate logistic regression analysis also demonstrated that $Sv_{O_2} \leq 70\%$, $Pa_{CO_2} \leq 40$ mmHg, and CVP ≥ 8 mmHg were likely predictors of the occurrence of jugular bulb desaturation.
Conclusion. Changes in Sv_{O_2} and Pa_{CO_2} were associated with jugular bulb oxygen saturation, and $Sv_{O_2} \leq 70\%$, $Pa_{CO_2} \leq 40$ mmHg, and CVP ≥ 8 mmHg had a significant odds ratio for jugular bulb desaturation. We suggest that achieving normal values of Sv_{O_2}, Pa_{CO_2}, and CVP may be important to prevent cerebral desaturation during OPCAB.

Key words Jugular bulb · Oxygen saturation · Off-pump · CABG · Mixed venous oxygen saturation

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Introduction

Cardiopulmonary bypass (CPB) is a routine element of cardiac surgery that results in a number of inevitable derangements. These include, but are not limited to, acute hemodilution, a systemic inflammatory response, and oxidative stress, as well as the activation of platelets and complement elicited by blood contact with the surface of the CPB circuit, which may leads to gaseous or particulate embolization [1–4]. Off-pump coronary artery bypass grafting surgery (OPCAB) could attenuate most of these events and has lately been introduced as a suitable alternative to circumvent these side-effects. While it may seem logical to assume that the elimination of CPB with OPCAB would reduce some of the cerebral injury associated with cardiac surgery, other mechanisms remain, and postoperative cognitive dysfunction is well documented in OPCAB patients [5–7]. Further, hemodynamic compromise due to manipulation of the heart by the surgeon has been associated with a significant decrease in jugular venous bulb oxygen saturation (Sj_{O_2}) [8,9] which, in turn, has been associated with cognitive decline [10,11]. Thus, impaired cerebral perfusion during OPCAB surgery is being discussed as a possible contributor to cerebral injury [7].

Sj_{O_2} is a useful monitor to evaluate global cerebral oxygen balance in patients following head injury [12–15] and during major cardiovascular procedures [10,16,17]. Jugular bulb desaturation ($Sj_{O_2} \leq 50\%$) is considered as a potential indicator of postoperative cognitive dysfunction (POCD) in conventional coronary artery bypass grafting (CABG) [10], but routine monitoring of Sj_{O_2} is invasive and expensive and may not be justified to be performed in all elective OPCABs. However, if other routinely monitored hemodynamic parameters such as mixed venous oxygen saturation (Sv_{O_2}), partial pressure of carbon dioxide (Pa_{CO_2}), or central venous pressure (CVP) could predict changes in Sj_{O_2}, these parameters could serve as cost-effective monitors for periods of cerebral oxygen imbalance. Therefore, we hypothesized that certain patterns in physiological parameters such as Sv_{O_2}, Pa_{CO_2}, and CVP are associated with jugular bulb desaturation during OPCAB surgery.

Patients and methods

Following institutional review board approval, written informed consent was obtained from 43 consecutive patients undergoing elective OPCAB surgery. Patients receiving dialysis, and those with arterial fibrillation and left ventricle ejection fraction less than 40% were excluded from this study. Anesthesia was induced by intravenous midazolam (0.1 $mg \cdot kg^{-1}$) and fentanyl (10 $\mu g \cdot kg^{-1}$), and vecuronium (0.15 $mg \cdot kg^{-1}$) was given prior to tracheal induction for muscular paralysis. Anesthesia was maintained by continuous infusion of propofol (6 $mg \cdot kg^{-1} \cdot h^{-1}$) and fentanyl (4 $\mu g \cdot kg^{-1} \cdot h^{-1}$), and intermittently vecuronium was administered intravenously if needed. After induction of anesthesia, the radial artery was cannulated to monitor arterial blood pressure and sample arterial blood. A 5.5-French fiberoptic oximeter catheter (Opticath; Abbott Laboratories, North Chicago, IL, USA) was inserted retrogradely into the right jugular bulb for analysis of Sj_{O_2}. The proper position of the tip of the catheter was confirmed by anteroposterior cervical spine fluoroscopy. The proper position is reached when the catheter tip is situated cranial to a line extending from the atlanto-occipital joint space and caudal to the lower margin of the orbit. A pulmonary artery catheter (OptiQ; Abbott Laboratories) was inserted via the right internal jugular vein for the sampling of mixed venous blood and to obtain and calculate hemodynamic parameters.

All surgical procedures were approached through a standard median sternotomy under general anesthesia. Before grafting to coronary arteries, 100 unit kg^{-1} of heparin was administered to keep activated clotting time between 250 and 350 s, determined by ACT II (Medtronic, Minneapolis, MN, USA). During the left anterior descending artery (LAD) anastomosis, stabilization of the LAD was accomplished with an Octopus 4 Tissue Stabilizer (Medtronic). In the circumflex branch (CX) or posterior descending artery (PDA) anastomosis, the Octopus 4 Tissue Stabilizer and a Starfish 2, and a heart positioner (Medtronic) were used. To further assist in providing good presentation of the target arteries, especially in the CX or PDA anastomoses, patients were placed in the Trendelenburg position where the operating table was tilted down to a 5° to 10° angle. While the patient was in the Trendelenburg position, the position of pressure transducers was adjusted to the height of the heart. Intracoronary shunts (ANASTAFLO; Edwards Life Science, Irvine, CA, USA), were used to maintain coronary flow. During the anastomosis, norepinephrine was administered as needed up to 0.1 $\mu g \cdot min^{-1} \cdot kg^{-1}$ to maintain mean arterial pressure of more than 60 mmHg.

Hemodynamic data including mean arterial blood pressure (MAP), heart rate, CVP, mean pulmonary artery pressure (MPAP), and cardiac index (CI) were recorded, and arterial, mixed venous, and jugular venous bulb blood gas analyses were performed with the ABL720 (Radiometer Medical, Brønshøj, Denmark) at the following points: (1) before anastomosis of the coronary artery; (2) during anastomosis of the LAD; (3) during anastomosis of the CX or PDA; and (4) after chest closure. Blood samples and hemodynamic data were obtained after sufficient hemodynamic stability was obtained at each point. Nasopharyngeal temperature was also monitored, with a Mon-a-therm 12-French temperature probe (Mallinckrodt, Hazelwood, MO, USA) and recorded as body temperature (BT).

To compare any differences of hemodynamic variables at the four selected time points, one-way analysis of variance with repeated measures was used, followed by Tukey and Kramer tests as a post-hoc analysis. To assess an association between Sj_{O_2} and intraoperative variables, including CVP, cerebral perfusion pressure (CPP; MAP − CVP), MAP, MPAP, Sv_{O_2}, Pa_{CO_2}, nasopharyngeal temperature, and CI, simple linear regression analysis based on univariate analysis was performed. Variables related to lower Sj_{O_2} on univariate analysis with $P < 0.10$ were entered into a multivariate linear regression analysis. Further, another univariate analysis was performed with a χ^2 test to assess the risk of jugular bulb desaturation. Physiological and hemodynamic variables were dichotomized as normal, or abnormal and then entered into a logistic regression analysis model. Also, as Polonen et al. [18] have demonstrated that a drop in Sv_{O_2} of less than 70% was associated with poor prognosis after cardiac surgery, and as a CI of less than 2.2 $l \cdot min^{-1} \cdot m^2$ has been used as a definition of low cardiac output syndrome [19–21], we selected Sv_{O_2} of 70% and CI of 2.2 $l \cdot min^{-1} \cdot m^2$ as the cutoff values. Those variables with $P < 0.10$ were again entered into a multivariate logistic regression analysis; differences were considered significant at $P < 0.05$.

Results

Patient demographics are shown in Table 1. Although 43 patients were enrolled in this study, 4 patients were excluded because of failure to either cannulate the jugular vein or to place the tip of the jugular venous bulb catheter at the appropriate position. Table 2 shows the physiological data by arterial blood gas analysis. There was a slight but significant decrease in pH during the anastomosis of the CX or PDA and in PO_2 after completion of all anastomoses. BT also decreased slightly but significantly during anastomosis of the CX or PDA. Hemodynamic data are shown in Table 3. CI decreased significantly during anastomosis of the CX or PDA. Hemoglobin concentrations were significantly lower during anastomosis of all coronary arteries. MAP decreased only during anastomosis of the LAD. CVP and MPAP increased significantly during anastomosis of the CX and the PDA. CPP decreased significantly after the baseline measurement and remained low even after completion of all anastomoses. Sj_{O_2} was significantly lower during anastomosis of the CX or PDA as compared to baseline. Sv_{O_2} also decreased significantly during anastomosis of the LAD, CX, or PDA compared to the baseline measurement.

As demonstrated in Table 4, based on simple linear regression analysis, changes in CVP, CI, Sv_{O_2}, and Pa_{CO_2} were significantly associated with Sj_{O_2}. Using multivariate linear regression analysis, Sv_{O_2} and Pa_{CO_2} were shown to be associated with Sj_{O_2} (multiple regression coefficient, r = 0.45; $Sj_{O_2} = -0.09{*}CVP - 0.02{*}CI + 0.28{*}Sv_{O_2} + 0.25{*}Pa_{CO_2}$), as shown in Table 5. Comparing physiological and hemodynamic variables, CVP ≥ 8 mmHg, CI ≤ 2.2 $l \cdot min^{-1} \cdot m^2$, Sv_{O_2} ≤ 70%, and Pa_{CO_2} ≤ 40 mmHg were significantly associated with jugular bulb desaturation by univariate analysis (Table 6). Multivariate logistic regression analysis revealed that three predictors; namely, CVP ≥ 8 mmHg, Sv_{O_2} ≤ 70%, and Pa_{CO_2} ≤ 40 mmHg were associated with jugular bulb desaturation (Table 7).

Table 1. Patients' characteristics (*n* = 39)

Age (years)	67 ± 9
Sex (M/F)	27/12
Height (cm)	160 ± 9
Weight (kg)	59 ± 9
BSA (m^2)	1.62 ± 0.16
Operation time (min)	286 ± 67
Diabetes (%)	72
HT (%)	77
EF ≥ 45% (%)	78
COPD (%)	3
Sj_{O_2} ≤ 50 % (%)	33

Data are expressed as means ± SD
BSA, body surface area; HT, hypertension; EF, ejection fraction; COPD, chronic obstructive pulmonary disease; Sj_{O_2}, jugular venous bulb oxygen saturation

Discussion

Hemodynamic compromise due to manipulation of the heart during OPCAB has previously been associated

Table 2. Physiological data (*n* = 39)

	Control	LAD	CX or PDA	After
pH	7.42 ± 0.04	7.42 ± 0.04	7.40 ± 0.04*	7.38 ± 0.04*
P_{CO_2} (mmHg)	38 ± 3	38 ± 3	38 ± 3	39 ± 2
P_{O_2} (mmHg)	188 ± 46	198 ± 42	205 ± 62	155 ± 38*
BT (C°)	36.3 ± 0.5	36.0 ± 0.5	35.8 ± 0.7*	35.9 ± 0.9

* $P < 0.05$ vs control values
Data are expressed as means ± SD
BT, body temperature; CX, circumflex branch; LAD, left anterior descending coronary artery; PDA, posterior descending coronary artery

Table 3. Hemodynamic and physiologic parameters

	Control	LAD	CX or PDA	After
Cardiac index ($l \cdot min^{-1} \cdot m^2$)	2.6 ± 0.7	2.4 ± 0.6	1.9 ± 0.5*	2.6 ± 0.7
Hemoglobin ($g \cdot dl^{-1}$)	10.0 ± 1.6	9.3 ± 1.5*	9.2 ± 1.2*	9.5 ± .75
MAP (mmHg)	77 ± 12	71 ± 11*	75 ± 9	70 ± 9*
CVP (mmHg)	7 ± 2	6 ± 3	12 ± 4*	6 ± 2
MPAP (mmHg)	16 ± 4	16 ± 3	21 ± 5*	16 ± 3
CPP (mmHg)	70 ± 12	64 ± 11*	63 ± 10*	64 ± 10*
Sj_{O_2} (%)	55 ± 10	54 ± 8	52 ± 8*	58 ± 9
Sv_{O_2} (%)	77 ± 6	73 ± 8*	66 ± 9*	75 ± 6
Sj_{O_2} ≤ 50% (%)	30.8	35.9	42.1	23.0

* $P < 0.05$ versus control
Data are expressed as means ± SD
CPP, cerebral perfusion pressure; CVP, central venous pressure; LAD, left anterior descending coronary artery; MAP, mean arterial pressure; MPAP, mean pulmonary artery pressure; PDA, posterior descending coronary artery; Sj_{O_2}, jugular bulb oxygen saturation; Sv_{O_2}, mixed venous oxygen saturation; Sj_{O_2} ≤ 50%, percentage of jugular bulb oxygen saturation measurements ≤50%

Table 4. Simple linear regression analysis of variables associated with Sj_{O_2}

Variables	Standardized coefficient	95% CI	*P* value
MAP (mmHg)	–0.05	–0.18–0.09	0.50
MPAP (mmHg)	–0.13	–0.57–0.05	0.11
CVP (mmHg)	–0.21	–0.89–0.12	0.01
CPP (mmHg)	0.02	–0.17–0.14	0.85
CI ($l \cdot min^{-1} \cdot m^2$)	0.17	0.11–4.23	0.04
Sv_{O_2} (%)	0.36	0.22–0.55	<0.01
Pa_{CO_2} (mmHg)	0.34	0.61–1.59	<0.01
BT (°C)	–0.03	–2.00–1.33	0.69
Hb ($g \cdot dl^{-1}$)	–0.09	–1.52–0.15	0.26

BT, body temperature; CPP, cerebral perfusion pressure; CI, cardiac index; 95% CI, 95% confidence interval; CVP, central venous pressure; Hb, hemoglobin; MAP, mean arterial pressure; MPAP, mean pulmonary artery pressure; Sv_{O_2}, mixed venous oxygen saturation

Table 5. Multivariate linear regression analysis for hemodynamic and physiological variables with *P* value <0.10 from univariate analysis

Hemodynamic variables	Adjusted covariate	95% CI	*P* value
CVP (mmHg)	–0.09	–0.64–0.15	0.22
CI ($l \cdot min^{-1} \cdot m^2$)	–0.02	–2.53–1.92	0.79
Sv_{O_2} (%)	0.28	0.11–0.52	0.00
Pa_{CO_2} (mmHg)	0.25	0.34–1.31	0.01

CI, cardiac index; 95% CI, 95% confidence interval; CVP, central venous pressure; Sv_{O_2}, mixed venous oxygen saturation

Table 6. Univariate χ^2 test when jugular bulb saturation ≤50 % in off-pump coronary artery bypass grafting (CABG)

Variables	χ^2	*P* value
MAP ≤ 60 mmHg	0.03	0.872
CPP ≤ 70 mmHg	1.21	0.27
CVP ≥ 8 mmHg	5.89	0.02
MPAP ≥ 20 mmHg	1.65	0.20
CI ≤ 2.2 $l \cdot min^{-1} \cdot m^2$	6.41	0.01
Sv_{O_2} ≤ 70%	11.13	0.00
Pa_{CO_2} ≤ 40 mmHg	5.81	0.02
BT ≤ 36°C	0.01	0.95
Hb ≤ 10 $g \cdot dl^{-1}$	0.10	0.75

BT, body temperature; CPP, cerebral perfusion pressure; CI, cardiac index; CVP, central venous pressure; Hb, hemoglobin; MAP, mean arterial pressure; MPAP, mean pulmonary artery pressure; Sv_{O_2}, mixed venous oxygen saturation

Table 7. Multivariate logistic regression analysis when jugular bulb saturation ≤ 50% in off-pump CABG

Variables	Odds ratio	95% CI	*P* value
CVP ≥ 8 mmHg	2.23	1.06–4.72	0.04
CI ≤ 2.2 $l \cdot min^{-1} \cdot m^2$	1.53	1.06–3.43	0.31
Sv_{O_2} ≤ 70%	2.49	1.06–5.88	0.04
Pa_{CO_2} ≤ 40 mmHg	3.74	1.16–12.02	0.03

CI, cardiac index; CVP, central venous pressure; Sv_{O_2}, mixed venous blood oxygen saturation

with periods of significant jugular venous bulb desaturation [8]. The present study confirmed these earlier findings during periods of cardiac displacement for anastomosis of the CX or PDA during OPCAB. While Sv_{O_2} and Pa_{CO_2} were significantly associated with Sj_{O_2} during OPCAB, this study also demonstrated that three factors, i.e., CVP ≥ 8 mmHg, Sv_{O_2} ≤ 70%, and Pa_{CO_2} ≤ 40 mmHg were significantly associated with jugular bulb desaturation in OPCAB surgery.

Our study is not the first to investigate whether mixed venous oxygenation or other physiological variables could serve as suitable surrogates of alterations in jugular bulb saturation in the context of cardiac surgery. In two studies employing conventional cardiopulmonary bypass (CPB), one in pediatric patients and one in adult patients undergoing cardiac surgery, no association between Sv_{O_2} and Sj_{O_2} was found [16,22]. The reason for this lack of an association during CPB still remains to be resolved. However, our study in OPCAB patients suggests, for the first time, that this relationship between mixed venous oxygenation and jugular bulb saturation may exist, at least in the absence of CPB. Further, our study showed Pa_{CO_2} to be associated with jugular venous bulb saturation. Pa_{CO_2} management during CPB is known to affect cerebral blood flow (CBF). Therefore, it does not come as a surprise that Pa_{CO_2} was demonstrated to have a significant relationship with Sj_{O_2} in our study.

Monitoring of the jugular venous bulb oxygen saturation has been shown to be useful in a number of settings [12–14], but its routine use in elective OPCAB patients cannot be justified, due to its associated cost and invasiveness. Our study suggests that the intraoperative assessment of Sv_{O_2} and Pa_{CO_2} during routine OPCAB may offer useful information predicting trends in Sj_{O_2} while Sj_{O_2} itself is not directly monitored.

The incidence of jugular bulb desaturation in our study (33%) was similar to that previously reported by Diephuis and colleagues [8], who also reported that jugular bulb desaturation occurred more frequently in OPCAB than in conventional CABG. In addition to the parameters of $Sv_{O_2} \leq 70\%$, and $Pa_{CO_2} \leq 40$ mmHg, our study also revealed that CVP ≥ 8 mmHg was significantly associated with jugular bulb desaturation. In regard to CVP, it is generally accepted that hemodynamic deterioration during OPCAB is due to the effect of cardiac displacement and inevitable pressure applied to the heart, both of which can affect ventricular function and coronary artery blood flow during anastomoses of the right coronary artery (RCA) or CX [23–25]. Kwak and colleagues [26] demonstrated that significantly reduced right ventricular ejection fraction accompanied by an increase of right ventricle afterload and decreased cardiac index (CI) were observed during heart displacement. Mathison and colleagues [27] suggested that increasing right ventricle end-diastolic pressure as a result of cardiac displacement was the major cause of hemodynamic change during OPCAB. Our result that CVP ≥ 8 mmHg had an association with jugular bulb desaturation during OPCAB appears to be in support of these findings. However, CVP values were easily elevated to more than 8 mmHg and a drop in Sv_{O_2} values to less than 70% could be seen during heart displacement in OPCAB [27,28]. These findings reflected the fact that jugular bulb desaturation occurred more frequently during OPCAB than during conventional CABG.

Some parameters that have been deemed to have an association with jugular bulb desaturation, i.e., CPP, MPAP, and CI, did not have a significant relationship with jugular bulb desaturation in our study. To keep CPP high would be important for preventing jugular bulb desaturation. However, CPP did not have a significant association with jugular bulb desaturation in the present study. CPP means the difference between MAP and CVP. During anastomosis of the PDA or CX, CVP elevation and MAP decrease could lead to a CPP reduction. However, norepinephrine was used to keep MAP high during anastomosis. As a result, CPP recovered, but CVP still remained high. Therefore, there may be no significant association between CPP and Sj_{O_2}. In regard to MPAP, reduced right ventricle ejection due to deformation of the right ventricle outlet did not increase MPAP. Therefore, MPAP did not have a significant association with jugular bulb desaturation. The reason why CI did not have a significant association with jugular bulb desaturation in our multivariate analysis is unknown. Other significant factors may be stronger than CI and lessen the significance of CI.

In their assessment of 48 patients undergoing OPCAB surgery, Kim and colleagues [9] reported that Sj_{O_2} remained within normal limits despite significant hemodynamic compromise. This result differs from the results of our study and implies that the global cerebral oxygen balance was maintained in their study. This difference might be explained, at least in part, by a different choice of anesthetic agents during OPCAB, with Kim and colleagues using isoflurane, which could lead to a higher Sj_{O_2} than propofol [29], which we used in our study. Diephuis and colleagues [8] and Yoda and colleagues [11] also used propofol as the anesthetic agent of choice during OPCAB, and both those studies describe significant jugular bulb desaturation during displacement of the heart in OPCAB surgery.

There were some limitations in the present study. First, in this study, patients with either diabetes mellitus or previous stroke were included. Previously impaired cerebral autoregulation might have an effect on jugular bulb desaturation. This potential effect on the association between Sj_{O_2} and Sv_{O_2} was not evaluated. Second, although this study showed significant associations, the overall number of patients was limited. With respect to the results of the logistic regression analysis, we are not in a position to rule out a possible effect of other factors that may have had an influence on jugular bulb desaturation. Consequently, our findings must be considered suggestive rather than conclusive.

Cerebral oxygen saturation (ScO_2) measured by near infrared spectroscopy (NIRS) may be one of the alternatives to Sj_{O_2}. However, previous studies failed to demonstrate a significant correlation between ScO_2 and Sj_{O_2} values [30–32]. There is wide individual variation in ScO_2 values because of the contamination of NIRS values by extracerebral blood flow, hemoglobin concentration, and the layer of cerebrospinal fluid [33]. In regard to Sj_{O_2}, there is a standard lower safety limit value, of less than 50%. On the other hand, there is no gold standard for the lower safety limit of ScO_2 values. Therefore, the percent change of ScO_2 from baseline could be useful in the clinical evaluation of cerebral oxygen balance, instead of its absolute values. It seems difficult to use ScO_2 values to detect cerebral desaturation.

In summary, the present study demonstrates that Sj_{O_2} and CI are significantly reduced during heart displacement in OPCAB surgery. Both Sv_{O_2} and Pa_{CO_2} showed a significant association with Sj_{O_2} during OPCAB surgery. $Sv_{O_2} \leq 70\%$, CVP ≥ 8 mmHg, and $Pa_{CO_2} \leq 40$ mmHg had significant associations with jugular bulb desaturation during OPCAB surgery. Maintaining normal values of

Sv_{O_2}, CVP, and Pa_{CO_2} may be important to prevent cerebral desaturation during OPCAB.

References

1. Abu-Omar Y, Balacumaraswami L, Pigott DW, Matthews PM, Taggart DP. Solid and gaseous cerebral microembolization during off-pump, on-pump, and open cardiac surgery procedures. J Thorac Cardiovasc Surg. 2004;127:1759–65.
2. Levy JH, Tanaka KA. Inflammatory response to cardiopulmonary bypass. Ann Thorac Surg. 2003;75:S715–20.
3. Murphy GJ, Angelini GD. Side effects of cardiopulmonary bypass: what is the reality? J Card Surg. 2004;19:481–8.
4. Cavalca V, Sisillo E, Veglia F, Tremoli E, Cighetti G, Salvi L, Sola A, Mussoni L, Biglioli P, Folco G, Sala A, Parolari A. Isoprostanes and oxidative stress in off-pump and on-pump coronary bypass surgery. Ann Thorac Surg. 2006;81:562–7.
5. Biancari F, Mosorin M, Rasinaho E, Lahtinen J, Heikkinen J, Niemela E, Anttila V, Lepojarvi M, Juvonen T. Postoperative stroke after off-pump versus on-pump coronary artery bypass surgery. J Thorac Cardiovasc Surg. 2007;133:169–73.
6. Van Dijk D, Jansen EW, Hijman R, Nierich AP, Diephuis JC, Moons KG, Lahpor JR, Borst C, Keizer AM, Nathoe HM, Grobbee DE, De Jaegere PP, Kalkman CJ. Cognitive outcome after off-pump and on-pump coronary artery bypass graft surgery: a randomized trial. JAMA. 2002;287:1405–12.
7. van Dijk D, Spoor M, Hijman R, Nathoe HM, Borst C, Jansen EW, Grobbee DE, de Jaegere PP, Kalkman CJ. Cognitive and cardiac outcomes 5 years after off-pump vs on-pump coronary artery bypass graft surgery. JAMA. 2007;297:701–8.
8. Diephuis JC, Moons KG, Nierich AN, Bruens M, van Dijk D, Kalkman CJ. Jugular bulb desaturation during coronary artery surgery: a comparison of off-pump and on-pump procedures. Br J Anaesth. 2005;94:715–20.
9. Kim JY, Kwak YL, Oh YJ, Kim SH, Yoo KJ, Hong YW. Changes in jugular bulb oxygen saturation during off-pump coronary artery bypass graft surgery. Acta Anaesthesiol Scand. 2005;49:956–61.
10. Croughwell ND, Newman MF, Blumenthal JA, White WD, Lewis JB, Frasco PE, Smith LR, Thyrum EA, Hurwitz BJ, Leone BJ. Jugular bulb saturation and cognitive dysfunction after cardiopulmonary bypass. Ann Thorac Surg. 1994;58:1702–8.
11. Yoda M, Nonoyama M, Shimakura T. Cerebral perfusion during off-pump coronary artery bypass grafting. Surg Today. 2004;34:501–5.
12. Gopinath SP, Valadka AB, Uzura M, Robertson CS. Comparison of jugular venous oxygen saturation and brain tissue PO2 as monitors of cerebral ischemia after head injury. Crit Care Med. 1999;27:2337–45.
13. Gupta AK, Hutchinson PJ, Al-Rawi P, Gupta S, Swart M, Kirkpatrick PJ, Menon DK, Datta AK. Measuring brain tissue oxygenation compared with jugular venous oxygen saturation for monitoring cerebral oxygenation after traumatic brain injury. Anesth Analg. 1999;88:549–53.
14. Imberti R, Bellinzona G, Langer M. Cerebral tissue PO2 and SjvO2 changes during moderate hyperventilation in patients with severe traumatic brain injury. J Neurosurg. 2002;96:97–102.
15. Oertel M, Kelly DF, Lee JH, McArthur DL, Glenn TC, Vespa P, Boscardin WJ, Hovda DA, Martin NA. Efficacy of hyperventilation, blood pressure elevation, and metabolic suppression therapy in controlling intracranial pressure after head injury. J Neurosurg. 2002;97:1045–53.
16. Croughwell ND, Frasco P, Blumenthal JA, Leone BJ, White WD, Reves JG. Warming during cardiopulmonary bypass is associated with jugular bulb desaturation. Ann Thorac Surg. 1992;53:827–32.
17. Souter MJ, Andrews PJ, Alston RP. Jugular venous desaturation following cardiac surgery. Br J Anaesth. 1998;81:239–41.
18. Polonen P, Ruokonen E, Hippelainen M, Poyhonen M, Takala J. A prospective, randomized study of goal-oriented hemodynamic therapy in cardiac surgical patients. Anesth Analg. 2000;90:1052–9.
19. Rao V, Ivanov J, Weisel RD, Ikonomidis JS, Christakis GT, David TE. Predictors of low cardiac output syndrome after coronary artery bypass. J Thorac Cardiovasc Surg. 1996;112:38–51.
20. Rao V, Ivanov J, Weisel RD, Cohen G, Borger MA, Mickle DA. Lactate release during reperfusion predicts low cardiac output syndrome after coronary bypass surgery. Ann Thorac Surg. 2001;71:1925–30.
21. Maganti MD, Rao V, Borger MA, Ivanov J, David TE. Predictors of low cardiac output syndrome after isolated aortic valve surgery. Circulation. 2005;112:I448–52.
22. Yeh T Jr, Gouldman J, Auden SM, Seremet V, Edmonds HL Jr, Cerrito PB, Austin EH3rd. Mixed venous oxygen saturation does not adequately predict cerebral perfusion during pediatric cardiopulmonary bypass. J Thorac Cardiovasc Surg. 2001;122:192–3.
23. Grundeman PF, Borst C, van Herwaarden JA, Mansvelt Beck HJ, Jansen EW. Hemodynamic changes during displacement of the beating heart by the Utrecht Octopus method. Ann Thorac Surg. 1997;63:S88–92.
24. Grundeman PF, Borst C, van Herwaarden JA, Verlaan CW, Jansen EW. Vertical displacement of the beating heart by the octopus tissue stabilizer: influence on coronary flow. Ann Thorac Surg. 1998;65:1348–52.
25. Nierich AP, Diephuis J, Jansen EW, Borst C, Knape JT. Heart displacement during off-pump CABG: how well is it tolerated? Ann Thorac Surg. 2000;70:466–72.
26. Kwak YL, Oh YJ, Jung SM, Yoo KJ, Lee JH, Hong YW. Change in right ventricular function during off-pump coronary artery bypass graft surgery. Eur J Cardiothorac Surg. 2004;25:572–7.
27. Mathison M, Edgerton JR, Horswell JL, Akin JJ, Mack MJ. Analysis of hemodynamic changes during beating heart surgical procedures. Ann Thorac Surg. 2000;70:1355–60; discussion 60–1.
28. Chang WI, Kim KB, Kim JH, Ham BM, Kim YL. Hemodynamic changes during posterior vessel off-pump coronary artery bypass: comparison between deep pericardial sutures and vacuum-assisted apical suction device. Ann Thorac Surg. 2004;78:2057–62.
29. Petersen KD, Landsfeldt U, Cold GE, Petersen CB, Mau S, Hauerberg J, Holst P, Olsen KS. Intracranial pressure and cerebral hemodynamics in patients with cerebral tumors: a randomized prospective study of patients subjected to craniotomy in propofol-fentanyl, isoflurane-fentanyl, or sevoflurane-fentanyl anesthesia. Anesthesiology. 2003;98:329–36.
30. Ali MS, Harmer M, Vaughan RS, Dunne JA, Latto IP. Spatially resolved spectroscopy (NIRO-300) does not agree with jugular bulb oxygen saturation in patients undergoing warm bypass surgery. Can J Anaesth. 2001;48:497–501.
31. Yamashita K, Kazui T, Terada H, Washiyama N, Suzuki K, Bashar AH. Cerebral oxygenation monitoring for total arch replacement using selective cerebral perfusion. Ann Thorac Surg. 2001;72:503–8.
32. Leyvi G, Bello R, Wasnick JD, Plestis K. Assessment of cerebral oxygen balance during deep hypothermic circulatory arrest by continuous jugular bulb venous saturation and near-infrared spectroscopy. J Cardiothorac Vasc Anesth. 2006;20:826–33.
33. Yoshitani K, Kawaguchi M, Miura N, Okuno T, Kanoda T, Ohnishi Y, Kuro M. Effects of hemoglobin concentration, skull thickness, and the area of the cerebrospinal fluid layer on near-infrared spectroscopy measurements. Anesthesiology. 2007;106:458–62.