Reversal of Decreases in Cerebral Saturation in High-risk Cardiac Surgery

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Objectives: To measure the incidence of cerebral desaturations during high-risk cardiac surgery and to evaluate strategies to reverse cerebral desaturations.

Design: Prospective observational study followed by a randomized controlled study with 1 intervention group and 1 control group.

Setting: Tertiary care center specialized in cardiac surgery.

Participants: All patients were scheduled for high-risk cardiac surgery, 279 consecutive patients in the prospective study and 48 patients in the randomized study.

Interventions: An algorithmic approach of strategies to reverse cerebral desaturations. In the control group, no attempts were made to reverse cerebral desaturations.

Measurements and Main Results: Cerebral saturation was measured using near-infrared reflectance spectroscopy. A decrease of 20% from baseline for 15 seconds defined cerebral desaturations. The success or failure of the interventions was noted. Demographic data were collected. Models for predicting the probability and the reversal of cerebral desaturations were based on multiple logistic regressions. In the randomized study, 12 hours of measurements were continued in the intensive care unit without interventions. Differences in desaturation load (% desaturation × time) were compared between groups. Half of the high-risk patients had cerebral desaturations that could be reversed 88% of the time. Interventions resulted in smaller desaturation loads in the operating room and in the intensive care unit.

Conclusions: Cerebral desaturations in high-risk cardiac surgery are frequent but can be reversed most of the time resulting in a smaller desaturation load. A large randomized study will be needed to measure the impact of reversing cerebral desaturations on patient's outcome.

KEY WORDS: NIRS, near-infrared spectroscopy, cardiac surgery, high-risk patients, algorithm, prospective study, randomized study, cerebral oxygen saturation, cerebral desaturation, intervention to reverse cerebral desaturation

OVER THE LAST DECADE, near-infrared reflectance spectroscopy (NIRS) has been used increasingly as a noninvasive device to monitor regional saturation and blood flow in the cerebral frontal region during cardiac surgery. Originally developed as a neurologic monitor,[1,2] decreases in NIRS values have been used to detect catastrophic cerebral events when more invasive monitors remain silent.[1,3] Also, NIRS has been useful in detecting patients at risk of early cognitive decline after cardiac surgery.[4-6]

Given this evidence, one would expect the use of NIRS technology to be prevalent in cardiac surgery patients. However this is not necessarily the case, as NIRS is often regarded as a "doom-and-gloom" monitor, the one which tells anesthesiologists that something is wrong with the patient but for which little can be done. In an attempt to use NIRS as an intervention monitor, a few randomized studies have used strategies to reverse decreases in values of regional cortical oxygen saturation (rSO_2) to measure its effect on outcome. In a major abdominal surgery, reversing decreases in rSO_2 values is associated with better postoperative Mini-Mental State Examination scores, in shorter lengths-of-stay in the postanesthesia care unit and in the hospital.[7] In cardiac surgery, reversing decreases in rSO_2 values is associated in a lower risk of major organ dysfunction.[8] However, others have failed to follow specific strategies to reverse cerebral desaturations during their study.[4] Thus evidence that significant decreases in rSO_2 values successfully can be reversed during cardiac surgery remains scarce. To consolidate a strategic approach for the reversal of decreases in rSO_2 values, a clinical algorithm based on 10 years of experience with NIRS technology in cardiac surgery was proposed.[3] Using this algorithm, the authors hypothesize that the majority of decreases in rSO_2 values during cardiac surgery can be reversed and that this reversal will reduce the total desaturation load of patients, calculated area of depth of desaturation over time. This measure consistently has been associated with bad outcome.[1] Therefore, the goal of the present study was 2-fold. First, the authors prospectively tested the efficacy of the algorithm to reverse decrease in rSO_2 values in consecutive patients undergoing high-risk cardiac surgery. Second, in a pilot study, the authors randomized patients to an intervention (INTERV) group (use of the algorithm) and a control (CONT) group (no intervention) to verify that the interventions actually resulted in a reduction of the desaturation load during the course of surgery and in the intensive care unit (ICU).

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METHODS

Subjects and Data Collection

Prospective Study

Institutional Ethics approval was obtained for the prospective part of the study. Consecutive patients requiring complex cardiac surgery with cardiopulmonary bypass (CPB) were included in the study regardless of comorbidities. High-risk surgery was defined as redo surgery, adult congenital surgery, thoracic aortic surgery with and without circulatory arrest, and combined procedures surgery. Combined surgery included coronary artery bypass graft (CABG) and valvular surgery or multiple valvular surgery or valvular and aortic surgery. Patients with a perioperative risk estimation score >15 using the Parsonnet score[9] also were included in the study regardless of the surgery intended. Exclusion criteria included patients under the age of 18, emergency surgery, first-order CABG surgery, and single-valve surgery in patients with a perioperative risk estimation score <15. Descriptive data were collated on the patients.

Randomized Pilot Study

The Institutional Ethics Board approved the randomized study, and informed consent was obtained from every patient. Inclusion and exclusion criteria were identical to the prospective study except for patients with planned circulatory arrest because the anesthesiologists and surgeons insisted on the use of NIRS in these cases. The patients were randomized in 2 groups: an INTERV group where the algorithm was followed to reverse decreases in rSO_2 values, and a CONT group where the NIRS values were hidden from the anesthesiologists.

Measurement of rSO_2 values and strategies to reverse significant decreases in rSO_2

Cerebral oxygen saturation was measured using near-infrared spectroscopy (NIRS, INVOS 4000) with the sensors placed on each side of the forehead of the patients, as previously described.[3] Baseline rSO_2 values were obtained with the patient in a supine position breathing a mixture of oxygen and air with nasal prongs. Significant decreases in rSO_2 values were defined as a decrease $>20\%$ from baseline lasting 15 seconds or more.[8]

The algorithmic approach for the reversal of significant decreases in rSO_2 has been described previously and is shown in Figure 1.[3] When a significant decrease in rSO_2 values occurs, an alarm is activated and the anesthesiologist in charge follows the algorithm in an attempt to reverse the desaturation. The neutral position of the head is verified as extreme rotations can hinder jugular venous return or carotid flow. During CPB, the position of the venous cannula is verified to rule out obstruction (step 1 in Fig 1). If the head and cannula are placed correctly (or not placed yet) and blood pressure (BP) is lower than 20% of the mean

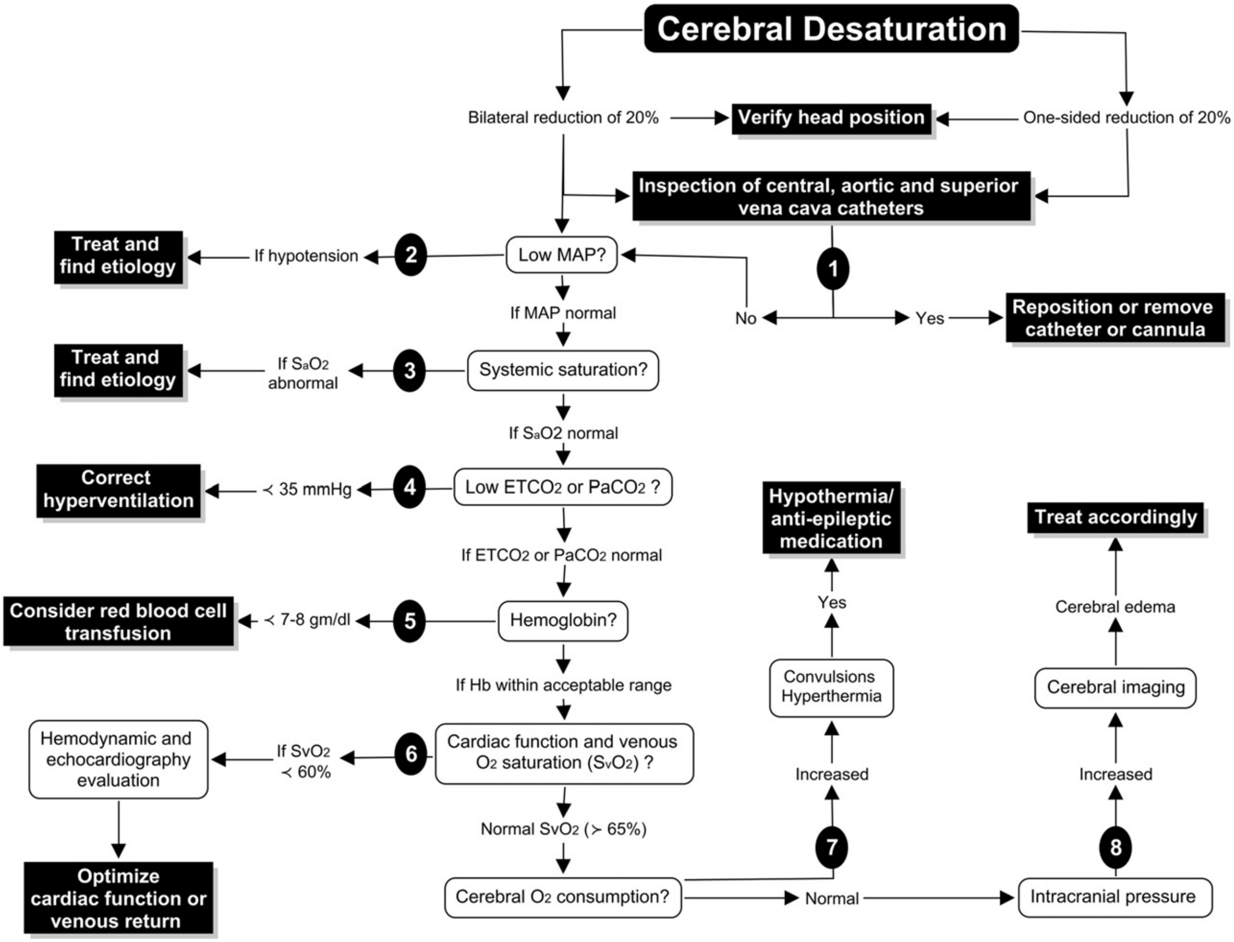

Fig 1. Algorithmic approach to the reversal of cerebral desaturations. MAP, mean arterial pressure; SaO_2, systemic arterial oxygen saturation by pulse oximetry; $PaCO_2$, partial pressure of arterial carbon dioxide; $ETCO_2$, end-tidal carbon dioxide concentration; Hb, hemoglobin; SvO_2, systemic venous oxygen saturation.

baseline for the patient, vasopressors or volume is given to increase BP (step 2 in Fig 1). If rSO_2 remains low after the increase in BP within 20% of the baseline, systemic oxygenation is verified with pulse oximetry and/or with the partial pressure of oxygen from an arterial blood gas (step 3 in Fig 1). If normal, end-tidal CO_2 is verified, and if below 35 mmHg, ventilator parameters are adjusted to increase end-tidal CO_2 between 35 and 45 mmHg (step 4 in Fig 1). When cerebral desaturation persists after the increase in end-tidal CO_2, hemoglobin levels are obtained and the anesthesiologists can transfuse the patient according to transfusion protocols (step 5 in Fig 1). When hemoglobin levels are above the lower limit for transfusion, the intervention is dependent on whether the patient is before, during, or after CPB. Before CPB, cardiac performance can be improved pharmacologically depending on the specific condition of the patient. During CPB, pump flow can be increased within acceptable levels. After CPB, right and left ventricular performance must be evaluated and cardiac performance improved depending on the specific findings (step 6 in Fig 1). Rarely, when cerebral desaturation is refractory, one can suspect hypothermia or a return to consciousness, or convulsions, and the patient should be treated according to the clinical findings (step 7 in Fig 1). With suspicion of an increase in intracranial pressure or cerebral ischemia in the interrogated region (step 8 in Fig 1), rSO_2 values are not expected to return to normal and proper investigation and treatment should be undertaken. Each intervention attempt and its success or failure is noted. As well, failure of the algorithmic approach to successfully reverse decreases in rSO_2 is recorded. Whether decreases in rSO_2 occurred before, during, or after CPB also is specified. All members of the anesthesiology department are familiar with the algorithm and participated in the study.

In the randomized trial, reversal of significant decreases in rSO_2 values was attempted as described earlier in the INTERV group, whereas in the CONT group the monitor screen was hidden and the alarms turned off but the rSO_2 values were saved for analysis. NIRS monitoring was maintained in the ICU in both INTERV and CONT for 12 hours or until endotracheal extubation. However, the monitor screen was hidden and the alarms turned off for all patients in the ICU.

Statistical Analysis

Prospective Study

Bivariate associations or comparisons were made using the Pearson correlation coefficients, 2-group t-tests, paired t-tests, and Pearson chi-square tests. Assumptions underlying the use of these procedures (such as linearity for the correlation coefficients, or normality and homoscedasticity of the variances for the 2-group t-test) were checked and transformations and/or nonparametric procedures were used when necessary.

Models for predicting the probability of a cerebral desaturation or the probability of reversing decreases in NIRS were based on multiple logistic regressions. A forward stepwise approach was used for selecting in a first step significant demographic variables. Adjusting for the significant demographic variables retained in the model, a second forward stepwise approach was done on the clinical variables. Adequacy of the models was verified with the Hosmer-Lemeshow statistic.

Randomized Pilot Study

Differences between the INTERV and CONT groups were analyzed using 2-group t-test for continuous data. Assumptions underlying the use of a t-test (normality and homoscedasticity of the variances) were checked, and transformations and/or nonparametric procedures were used when necessary. The Pearson chi-square test was used to compare groups for categorical data. The cerebral desaturation load in both the groups was calculated as the product of the time spent in desaturations and the severity of cerebral desaturations. Data are presented as means ± standard deviation unless otherwise specified, and statistical significance was set at $p < 0.05$. Q10

RESULTS

Prospective Observational Study

Incidence of Decreases in rSO_2 and Success Rate of Interventions

Descriptive data are presented in Table 1. Two hundred seventy-nine patients were included in the study, 159 men and 120 women. Baseline saturation values were similar between the right side and the left side. There was only a weak correlation between baseline values of cerebral saturation and the age of the patient ($r^2 = 0.064$). Baseline values of cerebral saturation were not significantly different in patients with a high Parsonnet score (>15) compared with patients with lower scores (67 ± 10% and 66 ± 10%, respectively, $p = 0.639$). Significant decreases in rSO_2 occurred in 48.8% of the patients, and reversal was achieved in 88.2% of them. In the 136 patients who had cerebral desaturations, a total of 267 desaturations were noted. Most patients had only 1 episode, 37 patients had 2, and 31 patients had more than 2 cerebral desaturations. The greatest number of cerebral desaturation in one patient was 9. Women had significantly more cerebral desaturations than men, 63% and 38%, respectively Q11 ($p < 0.0001$, relative risk = 1.629, confidence interval = 1.280-2.073).

A description of the interventions used and their success rate is described in Table 2. Interventions using the algorithmic T2 strategy resulted in the reversal of 235 of the 267 of the significant decreases in rSO_2 values, a success rate of 88.0%. The total number of interventions needed to achieve this result was 298, and thus, the rate of successful reversal per intervention is 78.9%. Half of the significant decreases in rSO_2 values occurred during CPB, and the rest of the desaturations were distributed equally between pre-CPB and post-CPB. Repositioning of the cannula and blood transfusions had a 100% rate

Table 1. Descriptive Data in the Prospective Observational Study

Number of patients	279
Men (%)	159 (57.0)
Women (%)	120 (43.0)
Age (y), mean (SD)	63.2 (14.2)
Height in cm, mean (SD)	166.8 (10.0)
Weight in kg, mean (SD)	76.1 (15.9)
Number of patients with the Parsonnet score >15 (%)	114 (40.9)
Baseline left rSO_2 values, mean (SD)	66.5 (10.7)
Baseline right rSO_2 values, mean (SD)	66.3 (11.0)
Number of patients with at least 1 desaturation (%)	136 (48.8)
Number of patients with successful reversal of desaturations (% reversal)	120 (88.2)
Number of patients with 2 desaturations (%)	37 (13.3)
Number of patients with >2 desaturations (%)	31 (11.1)
Men with cerebral desaturations/total number of men (%)	61/159 (38)
Women with cerebral desaturations/total number of women (%)	75/120 (63)

Abbreviation: SD, standard deviation.

Table 2. Overall Number of Cerebral Desaturations and Distribution of Interventions to Reverse Desaturations, Including the Success Rates During the Different Phases of Cardiac Surgery and in Total

	Pre-CPB	Per-CPB	Post-CPB	Total	% of all Interventions
Number of cerebral desaturations (% total)	67 (25.1)	134 (50.2)	66 (24.7)	267 (100)	
Number of interventions (% total)	71 (23.8)	150 (50.3)	77 (25.8)	298 (100)	
Number of successful reversal (% of desaturations)	59 (88.1)	126 (94.0)	50 (75.8)	235 (88.0)	
Increasing BP (2)/success (%)	20/18 (90.0)	61/56 (91.8)	21/18 (85.7)	102/92 (90.2)	34.2
Increasing $ETCO_2$ (3)/success (%)	29/27 (93.1)	11/4 (36.4)	15/7 (46.7)	55/38 (69.1)	18.2
Optimize cardiac function (6)/success (%)	0/0 (0%)	31/27 (87.1)	8/6 (75.0)	39/33 (84.6)	13.1
Blood transfusion (5)/success (%)	2/2 (100)	20/20 (100)	12/12 (100)	34/34 (100)	11.4
Change in head position (1)/success (%)	16/8 (50.0)	0/0	6/1 (16.7)	22/9 (40.9)	7.4
Repositioning of the cannula (1)/success (%)	4/4 (100)	15/15 (100)	0/0	19/19 (100)	6.4
Increase in F_IO_2 (3)/success (%)	0/0	12/4 (33.3)	6/1 (16.7)	18/5 (27.8)	6.0
Decrease in cerebral O_2 consumption (7)/success (%)	0/0	0/0	9/5 (55.6)	9/5 (55.6)	3.0

NOTE. Numbers in parentheses besides the intervention denote the step number in the algorithm in Figure 1.

Abbreviations: CPB, cardiopulmonary bypass; BP, blood pressure; $ETCO_2$, end-tidal carbon dioxide concentration; F_IO_2, fraction of inspired oxygen concentration; O_2, oxygen.

of success of reversal of cerebral desaturations. Following these, in decreasing order, the most successful interventions were increasing BP (90.2%), optimizing cardiac function (84.6%), increasing $PaCO_2$ (69.1%), decreasing cerebral oxygen consumption (55.6%), changing the position of the head (40.9%), followed by increasing the F_IO_2 (27.8%). Table 2 also describes the interventions most frequently used. By far, increases in BP were used the most often (34.2%) with an overall success rate over 90%, indicating that BP control is important for maintaining cerebral blood flow and oxygenation in this patient population. There was no treatment for suspected increases in intracranial pressure.

Table 3 describes the proportion of cerebral desaturations with the types of surgical interventions. The most frequent type of surgery was combined surgery (34.8%); this was followed in descending order by first-order CABG in patients with a perioperative risk estimate score >15, redo surgeries, mitral valve replacement or repair, aortic valve replacement, replacement of the ascending aorta, and tricuspid valve repair. More than 50% of the patients who underwent redo surgery, aortic valve replacement, ascending aorta repair, and aortic valve repair had a significant decrease in rSO_2 values. Patients for tricuspid valve repair had the least amount of decreases in rSO_2 value (30%).

Predictive Model of Cerebral Desaturation

The results from the predictive model of decreases in rSO_2 values as well as the success of the interventions to reverse cerebral desaturations are shown in Table 4. Overall, lower weight patients, female patients, and patients undergoing surgery other than mitral valve surgery were more at risk of cerebral desaturations. Q12 When specified during pre-, per-, and post-CPB, the predictive model showed that female was the only predictive factor for cerebral desaturations in the pre-CPB period. During CPB, female patients, lower weight patients, and patients undergoing redo surgery were more at risk of cerebral desaturations. No predictive factors were found for the period post-CPB.

The predictive model for the interventions most likely to succeed in reversing decreases in rSO_2 values showed that increasing BP or increasing end-tidal carbon dioxide concentration ($ETCO_2$) was the most successful interventions when adjusting for sex, redo surgery, and combined surgeries. Moving the head was the least likely intervention to reverse decreases in rSO_2 values.

Randomized Pilot Study

Forty-eight patients were recruited for the randomized pilot study: 25 control patients and 23 intervention patients. The incidence of cerebral desaturations was similar between the groups, 19/25 (76%) patients in the CONT group compared with 16/23 (69.6%) in the INTERV group. In the INTERV group, 92.5% of significant decreases in rSO_2 values were reversed back to normal values. When looking at the differences in the severity of cerebral desaturations in the operating room (OR) between the groups, the total area under the curve

Table 3. Distribution of the Type of High-Risk Surgeries and Association with the Occurrence of Cerebral Desaturations in the Operating Room

Type of Surgery	Number of Patients (% of all Surgeries)	Number of Patients With Desaturations (% for Type of Surgery)
Combined surgeries (excluding redo surgery)	107 (38.4)	47 (43.9)
Coronary artery bypass graft	53 (19.0)	24 (45.3)
Redo surgery	33 (11.8)	20 (60.6)
Mitral valve replacement or repair	30 (10.8)	16 (53.3)
Aortic valve replacement	23 (8.3)	14 (60.9)
Surgery of the ascending aorta	20 (7.2)	11 (55%)
Tricuspid valve repair	13 (4.7)	4 (30.8)

Table 4. Predictive Models of Cerebral Desaturations and of Reversal of Cerebral Desaturations

Parameters	b ± SE (b)	p Value	Odds Ratio
(A) Overall predictive model of cerebral desaturation			
Weight (kg)	−0.018 ± 0.008	0.027	0.982
Women	0.949 ± 0.258	$<$0.001	2.582
Mitral valve surgery	−0.572 ± 0.284	0.044	0.565
Intercept	1.094 ± 0.675	0.105	2.986
(B) Predictive model of cerebral desaturation pre-CPB			
Women	1.303 ± 0.331	$<$0.001	3.680
Intercept	−2.190 ± 0.264	$<$0.001	0.112
(C) Predictive model of cerebral desaturation per-CPB			
Weight (kg)	−0.017 ± 0.008	0.040	0.983
Women	0.626 ± 0.263	0.017	1.869
Redo surgery	0.832 ± 0.384	0.030	2.298
Intercept	0.313 ± 0.681	0.646	1.367
(D) Predictive model of reversal of cerebral desaturations			
Women	0.515 ± 0.307	0.093	1.674
Redo surgery	1.813 ± 0.511	$<$0.001	6.126
Combined surgeries	−0.607 ± 0.228	0.008	0.545
Increasing BP	1.313 ± 0.276	$<$0.0001	3.719
Increasing $PaCO_2$	1.095 ± 0.389	0.005	2.989
Moving the head	−1.116 ± 0.545	0.041	0.328
Intercept	−0.996 ± 0.405	0.014	0.370

NOTE. (A) Parameters associated with cerebral desaturations regardless of the time of surgery.

(B) Parameters associated with cerebral desaturations before cardiopulmonary bypass (CPB).

(C) Parameters associated with cerebral desaturations during CPB.

(D) Parameters associated with a successful reversal of cerebral desaturations.

of time-desaturation percentage was significantly greater in the
T5 CONT group compared with the INTERV group (Table 5).
There were no differences between the CONT group and the
INTERV group in demographic data, total time of surgery, time
of CPB, time of intubation, ICU and hospital length-of-stay,
T6 and postoperative complications (Table 6).

Patients who did not have cerebral desaturations in the OR did not have desaturations in the ICU. Of the 19 patients who had cerebral desaturations in the OR in the CONT group, 14 (73.7%) had desaturations in the ICU. For the INTERV group, significantly fewer patients had cerebral desaturations in the ICU after having desaturations in the OR, 6/16 (37.5%, $p < 0.0347$). The total area under the curve of time-desaturation percentage in the ICU was significantly greater in the CONT group compared with the INTERV group (Table 5).

Table 5. Differences in Desaturation Load (Product of % Cerebral Desaturation and Time, %desat min) Between the Control Group and the Intervention Group in the Operating Room (OR) and in the Intensive Care Unit (ICU)

Desaturation Load (%desat min)	Control (n = 25)	Intervention (n = 23)	p Value
OR mean (SD)	729.7 (1260.6)	154.3 (218.3)	0.041
ICU mean (SD)	856.6 (95.6)	324 (54.7)	0.030

Abbreviation: SD, standard deviation.

Table 6. Demographic Data and Perioperative Data in the Randomized Controlled Study

	Control (n = 25)	Intervention (n = 23)	p Value
Age (y), mean (SD)	70.2 (9.2)	71.1 (7.9)	0.724
Sex (men/women)	19/6	14/9	0.353
Height (cm), mean (SD)	67.6 (12.8)	166.7 (9.3)	0.833
Weight (kg), mean (SD)	82.3 (16.6)	77.8 (14.7)	0.411
LVEF (%), mean (SD)	58.0 (8.6)	54.5 (7.4)	0.274
Parsonnet score, mean (SD)	19.7 (8.7)	23.4 (6.7)	0.156
Length of surgery (min), mean (SD)	305.7 (71.5)	322.6 (159.2)	0.743
CPB time (min), mean (SD)	114.2 (36.4)	119.3 (39.6)	0.659
Mechanical ventilation (h), mean (SD)	24.9 (46.2)	21.6 (33.6)	0.785
ICU length-of-stay (h), mean (SD)	9.4 (49.3)	71.9 (54.4)	0.309
Hospital length-of-stay (h), mean (SD)	7.9 (3.2)	7.6 (5.4)	0.838

Abbreviation: SD, standard deviation.

DISCUSSION

This is the first study describing the success rate of strategies to reverse significant decreases in rSO_2 values during high-risk cardiac surgery. High-risk surgery patients were chosen because the use of NIRS technology is reserved to this group of patients in the authors' institution for economic reasons. This appears to be the case in most other tertiary centers in Canada as was discovered using an informal survey during a meeting of the Canadian Perioperative Anesthesia Clinical Trial group.[10] Thus, NIRS technology presently appears to be used mainly in high-risk cardiac surgery patients even though there is very little evidence of its benefits in this group of patients.

The results of the study confirm that cerebral desaturations are frequent in high-risk cardiac surgery and that a high success rate in the reversal cerebral desaturations is possible using an algorithmic approach. In studies including only CABG patients, 30% to 56% of the patients had cerebral desaturations.[4,8] The authors found that 50% of the cerebral desaturations occur during CPB. This is important because it emphasizes the need for a common approach from anesthesiologists and perfusionists to develop strategies for the reversal of cerebral desaturations during CPB. Therefore, training perfusionists in the management and in the development of strategies to reverse decreases in rSO_2 values appears to be crucial. A specific algorithm for the reversal of cerebral desaturations during CPB could be envisioned.

Recently, NIRS values at baseline and during cardiac surgery have been used as an index of the severity of disease. For example, significant cerebral desaturations during CABG surgery are associated with an increase in hospital length-of-stay,[4,8] in multiple-organ dysfunction,[8] and in postoperative delirium.[11] In contrast to other authors, a correlation between baseline rSO_2 values and an increase in the perioperative risk evaluation score was not found by the authors.[12] Low baseline rSO_2 values prior to surgery were associated with low EuroSCORE,[12] low left ventricular systolic[12,13] and diastolic function,[13] with an increased risk of postoperative delirium[11] and increased risk of 30-day and 1-year major morbidity and mortality.[12] This discrepancy most likely resulted from the fact that the patient population included only high-risk patients. Also, the sample size in this study was 3 times smaller as the purpose of the study was to validate the algorithmic approach to the reversal of decreases in NIRS values.

Verifying the position of the head is the first intervention on the algorithm. The results show that this first intervention was unlikely to be effective in reversing cerebral desaturations. This is not surprising as its effectiveness depends on clear evidence of venous congestion or arterial obstruction. Adjusting a misplaced cannula however had a 100% success rate. These situations were recognized mainly from a deficit in the blood volume in the reservoir and using transesophageal echocardiography to identify cannula misplacement. No other monitoring device normally used in the OR can warn of such events. Because mechanical obstructions can have catastrophic consequences for patients,[3] a careful examination of the head and face of the patients and verifying the position of the cannula using transesophageal echocardiography is warranted when cerebral desaturations occur.

The predictive model indicated that BP control was an important factor in maintaining normal rSO_2 values. This is an important point as there is no consensus on what optimal BP should be used during CPB. Prior to CPB, BP levels depend on many factors including the level of myocardial ischemia, the degree of valvular disease, or a history of cerebral vascular disease. Thus, at this stage, the range of BP necessary to maintain normal homeostasis in patients is more apparent. During CPB however, BP targets for specific patients are much more difficult to determine. As a general rule, mean BP is maintained between 60 and 70 mmHg. The authors' experience has shown that some patients require a mean BP well over 70 mmHg during CPB to maintain rSO_2 values within 20% of the baseline, whereas other patients maintain baseline rSO_2 values with a mean BP in the fifties. Furthermore, large gradients were found regularly between BP measurements from the radial artery and the femoral artery. Femoral systolic pressure gradients <25 mmHg can be found in 30% to 50% of the patients during CPB.[14] This evidence suggests that NIRS measurements during CPB can help to personalize BP targets for specific patients and situations.

The impact of varying $ETCO_2$ values on cerebral oxygen saturation has been well documented.[15,16] Hypercapnia increases cerebral blood flow and thereby increases rSO_2 values, whereas hypocapnia has the reverse effect. Accidental or purposeful hypocapnia can have negative effect in patients including poorer psychomotor performance, personality changes, increased coronary arterial spasms, and reperfusion injury.[17] NIRS monitoring often helps in giving early warning of inadvertent hyperventilation of anesthetized patients. As well, on occasion, ventilation parameters can be adjusted to maintain $ETCO_2$ at the upper limit of the normal values in an attempt to maintain normal rSO_2 values without causing hypercarbic cerebral vasodilatation.

Blood transfusions were 100% effective in reversing cerebral desaturations in this study. One reason for this success rate is most likely the result of giving blood products only when the lower threshold for transfusions was reached and tissue oxygenation was jeopardized. In situations where there is uncertainty about the necessity to transfuse a patient, the combination of significant cerebral desaturations and a low hemoglobin value can be a strong enough argument to give blood if this is the only parameter on the algorithm that is abnormal. The same low hemoglobin value with a normal cerebral saturation, on the contrary, may help in the decision to postpone blood transfusion. These results suggest that NIRS monitoring could help establish personalized blood transfusion thresholds in this patient population. In pediatric patients, NIRS values have been used in the past to evaluate the need for blood transfusion during cardiac surgery.[18,19]

Independent predictors of cerebral desaturations included lower weight patients and being female. Frail patients may be at higher risk of desaturations because frailty is a sign of advanced disease. At present, indexes of frailty are being studied to predict outcome in cardiac surgery.[20-22] At first, the authors interpreted the increase in the incidence of cerebral desaturations in women to lower body weight and a dilution effect of the priming of the CPB machine. However, being female turned out to be an independent predictor of cerebral desaturations in high-risk cardiac surgery. The exact reasons remain to be investigated and elucidated.

In the prospective study, 88% of all the cerebral desaturations in the patient population were reversed successfully. Although one could assume that the interventions attempted were responsible for the reversal of cerebral desaturations, this may not be the case. Factors that anesthesiologists may not be aware of could have been responsible for some or most of the reversals. To rule out this possibility, it is necessary to show that interventions to reverse decreases in rSO_2 values result in a decrease in the total time patients spend in cerebral desaturations compared with a group of patients without interventions. The authors, therefore, performed a pilot randomized controlled trial to test this hypothesis. The results from this study showed that interventions resulted in a significant decrease in the length of time and severity of cerebral desaturations in these patients, other factors being equal. This is an important validation of the algorithmic strategies as the desaturation load, defined as the product of the time spent in cerebral desaturations and the severity of desaturations, has been associated with worse outcomes.[4-6,8] However, it is noteworthy that even though interventions reduced the time spent in a state of desaturation, this did not result in a significant difference in intubation time, ICU and hospital length-of-stay or in perioperative complications.

In the randomized study, the authors also wanted to look at the incidence of cerebral desaturations in high-risk cardiac surgery patients after they are transferred to the ICU. This is the first study to follow the evolution of NIRS measurements from the OR to the ICU. It is interesting that although the number of patients studied was low, the authors found that patients who do not have cerebral desaturations in the OR do not have desaturations in the ICU. Of the patients who had cerebral desaturations in the OR, the ones in the CONT group had a significantly larger desaturation load in the ICU compared with patients in the INTERV group. As no interventions were made to reverse decreases in rSO_2 values in the ICU, interventions made in the OR appear to have a protective effect on cerebral desaturations in the ICU. If this result can be reproduced, it would be an additional incentive to implement strategies to maintain baseline cerebral saturations in the OR in this patient population.

There are several limitations to the present study. First, this is a relatively small study performed in a single tertiary center. Thus, it is important to design a multicenter feasibility study to ensure that the strategies to reverse significant decreases in rSO_2 values can be applied successfully in other centers. Such a study is already in progress (NCT01432184). Second, the present study was not powered to look at patient's outcome. If the feasibility study is positive, a large randomized multicenter study will be needed to measure major outcomes in this patient population. Also, the algorithmic approach used in this study is not all-inclusive and its use in several centers could lead to the development of alternative strategies for the reversal of decreases in rSO_2 values. Finally, previous studies have shown that factors such as local skin ischemia and the use of vasopressors can result in decreases in rSO_2 values that have little to do with cerebral oxygenation and blood flow.[23,24] Therefore, an overall assessment of the patient's condition is always recommended when evaluating decreases in rSO_2 values.

In summary, the authors have demonstrated a high incidence of cerebral desaturations in high-risk cardiac surgery and developed a successful approach to reversing these desaturations. This approach reduces the desaturation load of patients during high-risk cardiac surgery and appears to have a protective effect on the desaturation load in the ICU. A feasibility study is under way and a large randomized controlled study will be needed to measure the overall benefit of reversing low NIRS values during high-risk surgery. The timing of these studies is crucial as NIRS is used increasingly in cardiac surgery. Meanwhile, clear evidence of its benefits and cost-effectiveness for patients is still lacking.

REFERENCES

1. Taillefer MC, Denault AY: Cerebral near-infrared spectroscopy in adult heart surgery: Systematic review of its clinical efficacy. Can J Anesth 52:79-87, 2005
2. Wahr JA, Tremper KK, Samra S, et al: Near-infrared spectroscopy: Theory and applications. J Cardiothorac Vasc Anesth 10: 406-418, 1996
3. Denault A, Deschamps A, Murkin JM: A proposed algorithm for the intraoperative use of cerebral near-infrared spectroscopy. Semin Cardiothorac Vasc Anesth 11:274-281, 2007
4. Slater JP, Guarino T, Stack J, et al: Cerebral oxygen desaturation predicts cognitive decline and longer hospital stay after cardiac surgery. Ann Thorac Surg 87:36-44, 2009
5. Yao FSF, Tseng CCA, Ho CYA, et al: Cerebral oxygen desaturation is associated with early postoperative neuropsychological dysfunction in patients undergoing cardiac surgery. J Cardiothorac Vasc Anesth 18:552-558, 2004
6. de Tournay-Jetté E, Dupuis G, Bherer L, et al: The relationship between cerebral oxygen saturation changes and postoperative cognitive dysfunction in elderly patients after coronary artery bypass graft surgery. J Cardiothorac Vasc Anesth 25:95-104, 2011
7. Casati A, Fanelli G, Pietropaoli P, et al: Continuous monitoring of cerebral oxygen saturation in elderly patients undergoing major abdominal surgery minimizes brain exposure to potential hypoxia. Anesth Analg 101:740-747, 2005
8. Murkin JM, Adams SJ, Novick RJ, et al: Monitoring brain oxygen saturation during coronary bypass surgery: A randomized, prospective study. Anesth Analg 104:51-58, 2007
9. Bernstein AD, Parsonnet V: Bedside estimation of risk as an aid for decision-making in cardiac surgery. Ann Thorac Surg 69:823-828, 2000
10. Hall R, Beattie S, Cheng D, et al: Can we develop a Canadian Perioperative Anesthesiology Clinical Trials Group? Can J Anesth 57: 1051-1057, 2010
11. Schoen J, Meyerrose J, Paarmann H, et al: Preoperative regional cerebral oxygen saturation is a predictor of postoperative delirium in on-pump cardiac surgery patients: A prospective observational trial. Crit Care 15:R218, 2011
12. Heringlake M, Garbers C, Käbler JH, et al: Preoperative cerebral oxygen saturation and clinical outcomes in cardiac surgery. Anesthesiology 114:58-69, 2011
13. Paquet C, Deschamps A, Denault AY, et al: Baseline regional cerebral oxygen saturation correlates with left ventricular systolic and diastolic function. J Cardiothorac Vasc Anesth 22:840-846, 2008
14. Denault A, Deschamps A: Abnormal aortic-to-radial arterial pressure gradients resulting in misdiagnosis of hemodynamic instability. Can J Anesth 56:534-536, 2009
15. Leung TS, Tachtsidis I, Tisdall MM, et al: Estimating a modified Grubb's exponent in healthy human brains with near infrared spectroscopy and transcranial Doppler. Physiol Meas 30:1-12, 2009
16. Watzman HM, Kurth CD, Montenegro LM, et al: Arterial and venous contributions to near-infrared cerebral oximetry. Anesthesiology 93:947-953, 2000
17. Laffey JG, Kavanagh BP: Hypocapnia. N Engl J Med 347: 43-53, 2002
18. Miyaji K, Kohira S, Miyamoto T, et al: Pediatric cardiac surgery without homologous blood transfusion, using a miniaturized bypass system in infants with lower body weight. J Thorac Cardiovasc Surg 134:284-289, 2007
19. Ging AL St, Onge JR, Fitzgerald DC, et al: Bloodless cardiac surgery and the pediatric patient: A case study. Perfusion 23:131-134, 2008
20. Sündermann S, Dademasch A, Praetorius J, et al: Comprehensive assessment of frailty for elderly high-risk patients undergoing cardiac surgery. Eur J Cardiothorac Surg 39:33-37, 2011
21. Sündermann S, Dademasch A, Rastan A, et al: One-year follow-up of patients undergoing elective cardiac surgery assessed with the comprehensive assessment of frailty test and its simplified form. Interact Cardiovasc Thorac Surg 13:119-123. [discussion 123], 2011
22. Howell NJ, Freemantle N, Bonser RS, et al: Subtle changes in renal function are associated with differences in late survival following adult cardiac surgery. Eur J Cardiothorac Surg 41:e38-e42, 2012
23. Davie SN, Grocott HP: Impact of extracranial contamination on regional cerebral oxygen saturation: A comparison of three cerebral oximetry technologies. Anesthesiology 116:834-840, 2012 Q13
24. Meng L, Cannesson M, Alexander BS, et al: Effect of phenylephrine and ephedrine bolus treatment on cerebral oxygenation in anaesthetized patients. Br J Anaesth 107:209-217, 2011