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ORIGINAL ARTICLE

Significance of Regional Cerebral Oxygen Saturation Monitoring for Neurological Outcomes in Aortic Surgery

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Abstract

Background: Near-infrared spectroscopy (NIRS) is commonly used for monitoring regional cerebral oxygen saturation (rSO₂) during cardiac surgery, but its relationship with postoperative neurological complications is unclear. In aortic surgery, NIRS is thought to be useful for detecting cerebral hypoperfusion, including unilateral perfusion abnormalities. Considering recent similar applications, we investigated rSO₂ changes measured by NIRS during rewarming in aortic surgery and their association with transient neurological disorder (TND) and permanent neurological disorder (PND).

Methods: We retrospectively analyzed 58 patients who underwent aortic surgery. Bilateral rSO₂ values were recorded at 5-min intervals for 60 min after the start of rewarming. TND was defined as postoperative delirium or delayed emergence, and PND as newly identified cerebral lesions. A linear mixed-effects model was used to analyze the effect of Time, a Factor (TND or Normal; PND or non-PND), and their interaction on rSO₂ values.

Results: TND was observed in eight patients and PND in five. At the start of rewarming, the mean rSO₂ was 65.0 ± 10.1%. A greater decrease in rSO₂ was observed in the normal group than in the TND group, although without significant difference (right: -0.007 [-0.041, 0.075] vs. -0.052 [-0.091, -0.017], p = 0.082; left: 0.006 [-0.035, -0.073] vs. -0.047 [-0.07, -0.015], p = 0.070). Meanwhile, the PND group had a greater decrease in rSO₂ at 5 min than the non-PND group, although without significant difference (right: -0.053 [-0.077, -0.019] vs. -0.047 [-0.091, -0.014], p = 0.967; left: -0.051 [-0.074, 0.000] vs. -0.039 [-0.069, -0.013], p = 0.740). A linear mixed-effects model analysis showed a consistent physiological decline in rSO₂ across all groups during the first 30 min of rewarming, but this decline persisted for a longer duration (up to 60 min) in the PND group. A significant Time × Factor interaction was found in the PND/non-PND group for both the right (p < 0.001) and left hemispheres (p < 0.001). The negative coefficient for this interaction suggests that rSO₂ values in the PND group decreased at a significantly faster rate than in the non-PND group (right side: β = -1.984, 95% CI: [-3.236, -0.732], p < 0.001; left side: β = -1.928, 95% CI: [-3.313, -0.543], p < 0.001). A similar significant interaction was found in the TND/Normal group's right hemisphere (β = -1.149, 95% CI: [-2.313, -0.014], p = 0.014), but not the left (p = 0.147), suggesting a potential lateralized effect. The main effect of the Factor (PND/non-PND) was not statistically significant in either hemisphere (right: p = 0.120; left: p = 0.759).

Conclusion: Early changes in rSO₂ during rewarming were unreliable predictors of postoperative neurological complications. However, the duration and degree of the rSO₂ decline in patients with PND throughout the rewarming phase may be related to the severity of neurological impairment.

Keywords

Regional cerebral oxygen saturation, Near-infrared spectroscopy, Neurological disorder, Aortic surgery



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Introduction

Near-infrared spectroscopy (NIRS) is widely used to monitor regional cerebral oxygen saturation (rSO₂) during cardiac surgery to prevent postoperative cognitive dysfunction. However, the relationship between intraoperative rSO₂ levels and the development of postoperative cognitive dysfunction is unclear [1]. Intraoperative cerebral desaturation is reportedly associated with an increased risk of postoperative delirium, and interventions based on NIRS monitoring may lead to a reduction in the risk of both postoperative delirium and cognitive dysfunction [2]. Nonetheless, consensus on this issue has yet to be reached. Meanwhile, Japanese clinical guidelines for the use of near-infrared cerebral oximetry suggest that NIRS is useful for detecting cerebral hypoperfusion, including unilateral perfusion abnormalities during aortic surgery [3]. Here, we investigate the changes in rSO₂ values during the rewarming phase of aortic surgery and we examine the association with postoperative neurological outcomes.

Methods

We retrospectively analyzed 58 patients from our hospital who underwent aortic surgery between April 2018 and March 2021, in whom complete data on rSO₂ during the rewarming phase were available. Intraoperative NIRS monitoring was performed using the INVOS™ 5100C regional oximeter (Medtronic, Minneapolis, MN, USA). Adhesive sensors (INVOS™ Cerebral/Somatic Oximetry Adult Sensor) were applied bilaterally to the forehead to collect data. rSO₂ values were recorded at 5-min intervals for 60 min after the initiation of rewarming. The value at the start of rewarming was defined as the baseline, and we calculated the rate of change from this baseline.

The primary outcomes were transient neurocognitive disorder (TND) and permanent neurocognitive disorder (PND). TND was defined as postoperative delirium or delayed emergence, while PND was defined as newly identified lesions on postoperative head computed tomography or magnetic resonance imaging. The TND and PND groups did not include any overlapping cases. The control group for TND was defined as all cases other than those with PND (Normal group), and the control group for PND was defined as all cases other than those with PND (non-PND group).

We performed Mann-Whitney U test to analyze rSO₂ changes in the initial 5 min. A linear mixed-effects model analysis was conducted to evaluate the effects of cerebral rSO₂ during the rewarming period on neurological outcome, defined as TND and PND. The model included Factor (TND/Normal or PND/non-PND), Time, and their interaction as fixed effects. All analyses were conducted with a significance level of $p < 0.05$.

Results

Surgical procedures included total arch replacement in 43 patients, partial arch replacement in nine patients, hemiarch replacement in four patients and ascending aortic replacement with open distal anastomosis in two patients. The mean cardiopulmonary bypass time was 156.7 ± 51.5 min. The target rectal temperature during circulatory arrest was 28°C, and the actual minimum rectal temperature was 25.4 ± 1.4 °C (Table 1).

Open distal anastomosis was performed under antegrade cerebral perfusion (ACP; duration: 67.3 ± 32.6 min) or combined retrograde and antegrade cerebral perfusion (RCP + ACP; retrograde perfusion time: 18.3 ± 12.5 min). Rewarming was initiated after completion of the distal anastomosis (rewarming time: 91.0 ± 31.5 min) (Table 2).

TND was observed in eight patients, all of whom exhibited postoperative delirium; none showed delayed emergence. PND occurred in five patients, comprising one case of right-sided cerebral infarction and four cases of bilateral multiple cerebral infarctions. One patient with preoperative cervical branch vessel dissection showed no neurological complications and was categorized in the Normal and non-PND groups.

Table 1: Clinical features of the participants.

Age, years	71.8	± 9.6
Male, n (%)	41	(70.7)
Etiology		
Aortic dissection/ dissected aneurysm	26	(44.8)
True aneurysm	31	(53.4)
Prosthetic vascular graft infection	1	(1.7)
Comorbidity		
Hypertension, n (%)	42	(72.4)
Dyslipidemia, n (%)	25	(43.1)
Diabetes, n (%)	9	(15.5)
History of neurological disease, n (%)	10	(17.2)
History of heart disease, n (%)	7	(12.1)
Chronic kidney disease, n (%)	6	(10.3)
Hemodialysis, n (%)	1	(1.7)
Cerebrovascular disease, n (%)	0	(0)
Asthma, n (%)	3	(5.2)
COPD, n (%)	2	(3.4)
Steroid administration, n (%)	1	(1.7)
Known dementia, n (%)	1	(1.7)
Preoperative status		
Cardiopulmonary resuscitation, n (%)	0	(0)
Cardiogenic shock, n (%)	1	(1.7)
Acute coronary syndrome, n (%)	1	(1.7)
Cerebral infarction	0	(0)
Consciousness disorder, n (%)	1	(1.7)
Transient ischemic attack, n (%)	1	(1.7)
Dissection involving cervical branches	1	(1.7)
Shaggy aorta, n (%)	1	(1.7)
Preoperative MRI (n = 47)		
Chronic ischemic white matter changes, n (%)	11	(23.4)

COPD: Chronic Obstructive Pulmonary Disease

Table 2: Operative details and outcomes

Emergency surgery, n (%)	12	(20.7)
Redo operation, n (%)	2	(3.4)
Operation		
Total arch replacement, n (%)	43	(74.1)
Hemiarch replacement, n (%)	9	(15.5)
Partial arch replacement, n (%)	4	(6.9)
Ascending aorta replacement, n (%)	2	(3.4)
Concomitant operation*, n (%)	32	(55.2)
Coronary artery bypass grafting, n (%)	14	(24.1)
Aortic valve replacement, n (%)	3	(5.2)
Aortic valvuloplasty, n (%)	2	(3.4)
Mitral valve replacement, n (%)	1	(1.7)
Mitral valve plasty, n (%)	3	(5.2)
Mitral annuloplasty, n (%)	1	(1.7)
Tricuspid annuloplasty, n (%)	6	(10.3)
Valve-sparing aortic root replacement, n (%)	4	(6.9)
Bentall, n (%)	2	(3.4)
Sinotubular junction plication, n (%)	5	(8.6)
Others, n (%)	13	(22.4)
Operative data		
Operation time, min	349.4	± 94.4
Cardiopulmonary bypass time, min	156.7	± 51.5
Aortic cross clamp time, min	80.4	± 46.3
Circulatory arrest time, min	29.8	± 10.7
Cerebral perfusion		
None, n (%)	3	(5.2)
Antegrade, n (%)	50	(86.2)
Retrograde, n (%)	5	(8.6)
Antegrade cerebral perfusion time, min	73.6	± 26.3
Retrograde cerebral perfusion time, min	18.3	± 12.5
Lowest rectal temperature, °C	25.4	± 1.4
Rewarming time, min	91.0	± 31.5
Postoperative neurological complications		
TND, n (%)	8	(13.8)
PND, n (%)	5	(8.6)
In-hospital death, n (%)	0	(0.0)

TND: Transient Neurological Disorder; PND: Permanent Neurological Disorder; *: Duplicate cases are listed across different procedures

At the beginning of rewarming, the mean rSO₂ was 65.0% ± 10.1%. At 5 min after the start of rewarming, rSO₂ values in the TND group were higher than those in the Normal group, but without significant difference (right: 69.0 [61.8 - 75.0] vs. 63.0 [59.0 - 67.0], *p* = 0.079; left: 68.5 [65.0 - 72.3] vs. 66.0 [59.0 - 70.0], *p* = 0.290). A greater decrease in rSO₂ was observed in the Normal group than in the TND group, although without significant difference (right: -0.007 [-0.041 - 0.075] vs. -0.052 [-0.091 - -0.017], *p* = 0.082; left: 0.006 [-0.035 - 0.073] vs. -0.047 [-0.07 - -0.015] ± 0.138, *p* = 0.070) (Table 3a).

In contrast, although not statistically significant, a greater decrease in rSO₂ at 5 min was observed in the PND group than in the non-PND group (right: -0.053 [-0.077, -0.019] vs. -0.047 [-0.091, -0.014], *p* = 0.967; left: -0.051 [-0.074, 0.000] vs. -0.039 [-0.069, -0.013], *p* = 0.740) (Table 3b).

Line plots of the mean rSO₂ values at each time point for each group are shown in Figure 1. All values were measured at 5-min intervals for up to 60 min after the start of rewarming. The temporal changes in rSO₂ in the TND and Normal groups are shown in figure 1A and in the PND and non-PND groups in figure 1B, separately for the left and right hemispheres. Differences in rSO₂ trends were observed between the PND and non-PND groups (Figure 1B).

The inclination of rSO₂ change from 10 min after the start of rewarming onward was analyzed using a linear mixed-effects model (Table 4). For the initial 30 min of rewarming, a significant time-dependent decrease in rSO₂ was observed across all groups (right side: TND group: β = -2.074, 95% CI [-2.809, -1.339], *p* < 0.001; PND group: β = -2.121, 95% CI [-2.774, -1.468], *p* < 0.001; left side: TND group: β = -1.668, 95% CI [-2.587, -0.749], *p* < 0.001; PND group: β = -1.788, 95% CI [-2.605, -0.972], *p* < 0.001) (Table 4a). However, no significant differences in intercepts (initial rSO₂ values) or incline (rate of change over time) were found between each outcome group and its respective control (Table 4a).

In analysis of right-sided rSO₂ changes up to 60 min after rewarming (Table 4b), the TND group showed a significantly higher initial value than in the Normal group (*p* = 0.048). Although the main effect of time was not significant (*p* = 0.736), a significant time × outcome interaction indicated a greater decline in rSO₂ over time in the TND group (β = -1.149, 95% CI: -2.313 to -0.014, *p* = 0.014).

In the PND group, there were no significant differences in initial right rSO₂ values (*p* = 0.120) or the main effect of time (*p* = 0.173). However, the time × outcome interaction was significant, showing a greater decrease over time than in the normal group (β = -1.984, 95% CI: -3.236 to -0.732, *p* < 0.001). Similarly, for left-sided rSO₂, no significant difference was observed in initial values between the PND and normal groups (*p* = 0.759), nor was the main effect of time significant (*p* = 0.125). However, the time × outcome interaction was again significant, with a greater decline over time in the PND group (β = -1.928, 95% CI: -3.313 to -0.543, *p* < 0.001).

Discussions

Generally, frontal rSO₂ has been considered as not directly reflecting deep cerebral ischemia or cerebral oxygen metabolism, and it does not represent global brain oxygenation. However, previous studies have suggested that cerebral injury may be associated with absolute decreases in rSO₂ as < 60%, reductions to 65-80% of baseline, or the appearance of interhemispheric differences [4-6]. Consequently, intraoperative cerebral oximetry is often used as a monitoring tool in cardiac and aortic surgery.

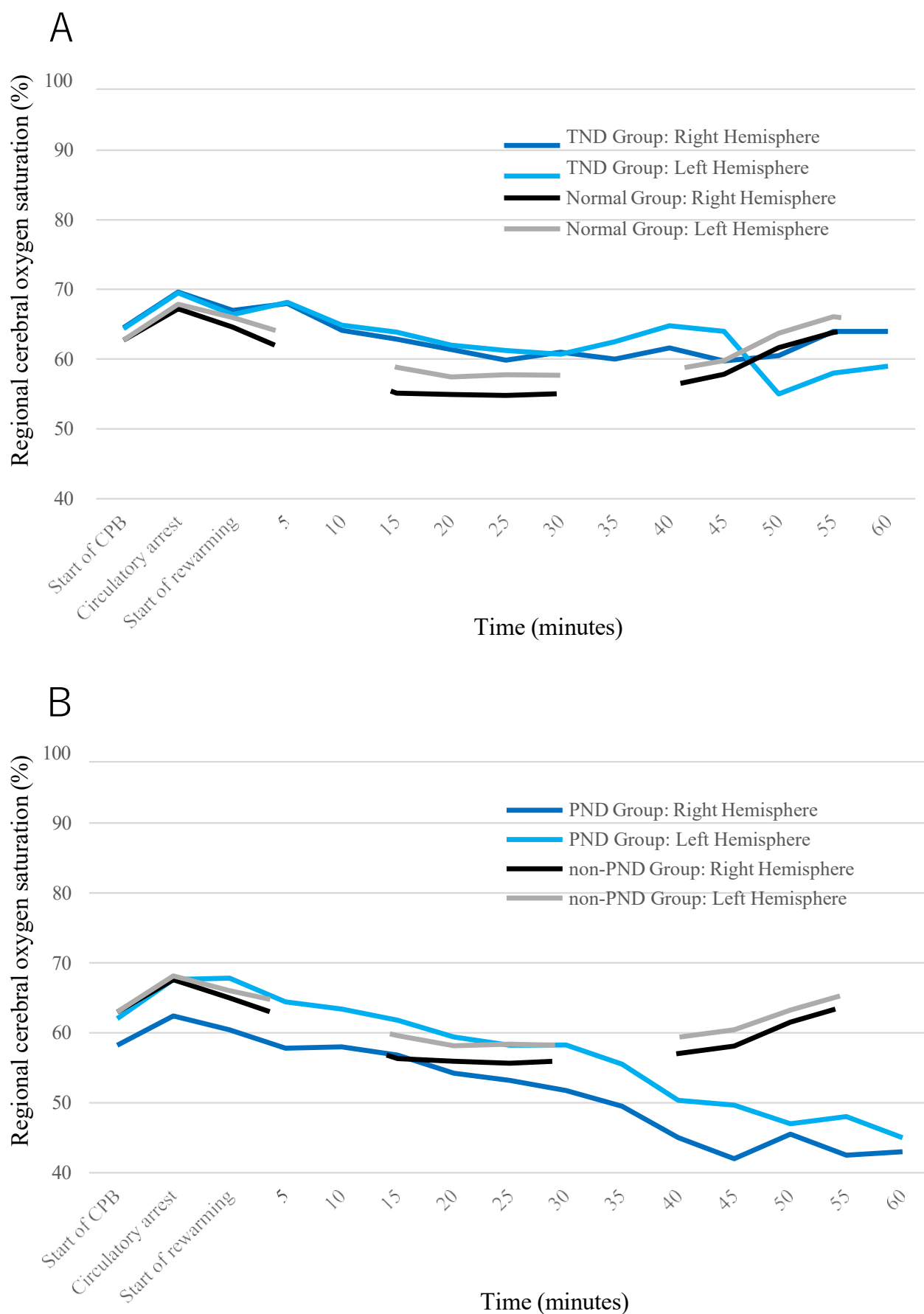


Figure 1: Line plots of the mean rSO₂ values at each time point for each group. All values were measured at 5-min intervals for up to 60 min after the start of rewarming. (A): The figure shows the temporal changes in rSO₂ in the transient neurological dysfunction (TND) and normal groups, separately for the left and right hemispheres; (B): The figure shows the temporal changes in rSO₂ in the permanent neurological disorder and non- permanent neurological disorder groups, separately for the left and right hemispheres.

Table 3: Comparison of regional cerebral oxygen saturation (rSO₂) at 5 minutes after the start of rewarming on neurological outcomes. The Mann-Whitney U test was used for statistical analysis.

Table 3a: Comparison of rSO₂ absolute values and relative changes between TND and Normal groups.

	Outcome Group	rSO ₂ Absolute Value (%) Median [IQR]	p-value	rSO ₂ Change (ΔrSO ₂) Median [IQR]	p-value
Right	TND (n = 8)	69.0 [61.8-75.0]	0.079	-0.007 [-0.041, 0.075]	0.082
	Normal (n = 45)	63.0 [59.0-67.0]		-0.052 [-0.091, -0.017]	
Left	TND (n = 8)	68.5 [65.0-72.3]	0.290	0.006 [-0.035, 0.073]	0.070
	Normal (n = 45)	66.0 [59.0-70.0]		-0.047 [-0.071, -0.015]	

rSO₂: Regional Cerebral Oxygen Saturation; TND: Transient Neurological Disorder; IQR: Interquartile Range

Table 3b: Comparison of rSO₂ absolute values and relative changes between PND and non-PND groups.

	Outcome Group	rSO ₂ Absolute Value (%) Median [IQR]	p-value	rSO ₂ Change (ΔrSO ₂) Median [IQR]	p-value
Right	PND (n = 5)	58.0 [54.0–60.0]	0.078	0.053 [-0.077, -0.019]	0.967
	No PND (n = 53)	64.0 [60.0–68.0]		-0.047 [-0.091, -0.014]	
Left	PND (n = 5)	64.0 [63.0–66.0]	0.647	-0.051 [-0.074, 0.000]	0.740
	No PND (n = 53)	67.0 [59.0–70.0]		-0.039 [-0.069, -0.013]	

rSO₂: Regional Cerebral Oxygen Saturation; PND: Permanent Neurological Disorder; IQR: Interquartile Range

Table 4a: Analysis from the start of rewarming to 30 minutes.

	TND / Normal			PND / non-PND		
	Fixed Effect [95% CI]	p-value		Fixed Effect [95% CI]	p-value	
Right cerebral rSO ₂						
Factor	7.72	[-4.896, 20.336]	0.132	3.814	[-11.371, 18.999]	0.535
Time	-2.074	[-2.809, -1.339]	< 0.001	-2.121	[-2.774, -1.468]	< 0.001
Time × Factor	-0.304	[-2.141, 1.532]	0.683	-0.006	[-2.203, 2.191]	0.994
Left cerebral rSO ₂						
Factor	5.5	[-14.690, 25.690]	0.501	-2.197	[-25.930, 21.536]	0.818
Time	-1.668	[-2.587, -0.749]	< 0.001	-1.788	[-2.605, -0.972]	< 0.001
Time × Factor	-0.767	[-3.082, 1.549]	0.413	-0.239	[-3.009, 2.531]	0.830

CI: Confidence Interval; TND: Transient Neurological Disorder; PND: Permanent Neurological Disorder;
rSO₂: Regional Cerebral Oxygen Saturation

Table 4b: Analysis from the start of rewarming to 60 minutes.

	TND / Normal			PND / non-PND		
	Fixed Effect [95% CI]	p-value		Fixed Effect [95% CI]	p-value	
Right cerebral rSO ₂						
Factor	10.4836	[-2.677, 23.643]	0.048	9.716	[-5.788, 25.221]	0.120
Time	-0.0586	[-0.486, 0.369]	0.736	-0.214	[-0.604, 0.176]	0.173
Time × Factor	-1.1496	[-2.313, 0.014]	0.014	-1.984	[-3.236, -0.732]	< 0.001
Left cerebral rSO ₂						
Factor	5.8736	[-14.523, 26.269]	0.475	2.931	[-20.822, 26.685]	0.759
Time	-0.1666	[-0.643, 0.311]	0.389	-0.267	[-0.699, 0.165]	0.125
Time × Factor	-0.7776	[-2.106, 0.552]	0.147	-1.928	[-3.313, -0.543]	< 0.001

CI: Confidence Interval; TND: Transient Neurological Disorder; PND: Permanent Neurological Disorder; rSO₂: Regional Cerebral Oxygen Saturation

An analysis of randomized trial data found no significant association between intraoperative reductions in rScO₂ and the development of postoperative cognitive dysfunction, including measures such as absolute values, cumulative duration of > 10% reduction from baseline, or relative changes [1]. Conversely, a recent systematic review and meta-analysis reported that cerebral oximetry monitoring was associated with a reduced incidence of postoperative cognitive dysfunction after cardiac surgery, but no significant association was found for postoperative delirium or stroke [2]. However, these results should

be interpreted with caution, owing to limitations in the quality of evidence.

In aortic surgery, monitoring changes in rSO₂ allows for early detection of perfusion abnormalities, such as misplacement of perfusion cannulas or localized cerebral hypoperfusion. Prompt corrective measures based on such findings have been reported to prevent cerebral injury [7,8]. In particular, rSO₂ has been shown to be a useful indicator for early detection of cerebral malperfusion and for deciding whether to convert from unilateral to bilateral antegrade cerebral perfusion (ACP) [9].

One study reported that a $\geq 4.6\%$ decrease in rSO_2 at 10 min after rewarming initiation was a predictor of delayed awakening and was associated with TND after total arch replacement [10].

Conversely, in present study, comparison of rSO_2 change rates at the first 5 min of rewarming showed no differing trends between outcome groups (Table 3a and 3b). A linear mixed-effects model showed a significant interaction between Time and Factor for the PND and non-PND group in both the right cerebral rSO_2 ($p < 0.001$) and left cerebral rSO_2 ($p < 0.001$) (Table 4b). For the TND and Normal groups, the interaction between Time $\times$ Factor was significant for the right cerebral rSO_2 ($p = 0.014$), but not for the left ($p = 0.147$).

Our findings indicate that while initial rSO_2 changes may not predict neurological outcomes, the temporal trend of rSO_2 during rewarming may provide valuable information. The significant Time $\times$ Factor interaction observed in the PND group suggests that a faster rate of rSO_2 decline is associated with the development of PND.

This study is limited by its comparatively small sample size, so individual patient factors may have influenced the results, particularly as the number of cases within each outcome group decreased over time during the rewarming phase. Further studies with larger cohorts are needed to validate these findings.

Conclusion

Early changes in rSO_2 during the rewarming phase in aortic surgery may not predict postoperative neurological complications. The decline in rSO_2 from 10 to 30 min that was observed across all groups may represent a physiological response. However, in the PND group, decline of rSO_2 persisted up to 60 min. The degree and duration of rSO_2 decline during rewarming may therefore change according to the severity of neurological impairment.

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