



Cerebral regional oxygen saturation as a predictive parameter for preoperative heart failure and delayed hemodynamic recovery in transcatheter aortic valve implantation: a retrospective cohort study

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Abstract

This study aimed to investigate the relationship of perioperative cerebral regional oxygen saturation (rSO₂) with various preoperative clinical variables and hemodynamic changes during transfemoral transcatheter aortic valve implantation (TAVI) under general anesthesia. We retrospectively analyzed cerebral rSO₂ values from left-hemisphere measurements obtained using near-infrared spectroscopy (O3™ regional oximetry) at five time points: pre-induction, the start of the procedure, the start of valve deployment, time of lowest cerebral rSO₂ value during valve deployment, and the end of the procedure. This study included 91 patients (60 with balloon-expandable valves and 31 with self-expandable valves). The baseline cerebral rSO₂ values were correlated with B-type natriuretic peptide, hemoglobin, fractional shortening, ejection fraction, left ventricular mass index, left ventricular end-systolic diameter, STS risk of mortality, and STS morbidity or mortality. The patients who took longer to recover their systolic blood pressure to 90 mmHg after valve deployment with a balloon-expandable valve (group B) had lower cerebral rSO₂ values during deployment compared to patients with faster recovery with balloon-expandable valve (group A) and with self-expandable valve (group C). Baseline cerebral rSO₂ is associated with preoperative variables related to cardiac failure and function, and a significant decline during valve deployment may indicate a risk of prolonged hypotension during TAVI.

Keywords Transcatheter aortic valve implantation · Cerebral regional oxygen saturation · Near-infrared spectroscopy · Valve deployment · Aortic stenosis · B-type natriuretic peptide

1 Introduction

Cerebral regional oxygen saturation (rSO₂) has been used as a non-invasive monitor to assess the adequacy of cerebral oxygen delivery in patients undergoing cardiac surgery, non-cardiac surgery, and cardiopulmonary resuscitation [1–5]. Low cerebral rSO₂ has been widely reported as a predictive factor associated with adverse clinical conditions, cognitive decline, mortality, and morbidity [6–9]. Meanwhile, the relationship between preoperative clinical variables and cerebral rSO₂ values is scarcely studied, and the predictive

ability of cerebral rSO₂ for delayed hemodynamic recovery in transcatheter aortic valve implantation (TAVI) has not been evaluated.

TAVI, an established minimally invasive procedure, is a therapeutic option for patients who require aortic valve surgery but are at high risk for surgical valve replacement or are inoperable. TAVI may be performed for frail elderly patients with symptomatic severe aortic stenosis (AS) [10–12]. However, in a TAVI procedure, significant fluctuations in cerebral rSO₂ values occur with balloon aortic valvuloplasty and valve deployment [13, 14]. Nevertheless, the association of cerebral rSO₂ values measured by O3™ regional oximetry with preoperative clinical variables and prolonged hypotension related to valve deployment has been scarcely investigated. We evaluated the association of cerebral rSO₂ with preoperative transthoracic echocardiography (TTE) variables, laboratory data, Society of Thoracic Surgeons (STS) score, Euro Score II, and hemodynamic

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changes during TAVI. Additionally, we investigated whether cerebral rSO₂ during TAVI could predict recovery from prolonged hypotension. Specifically, the primary objective was to investigate the association between cerebral rSO₂ and preoperative clinical variables in patients undergoing TAVI. The secondary objective was to determine whether cerebral rSO₂ could be a predictive factor for intraoperative hemodynamic compromise during TAVI.

2 Methods

2.1 Study design and patients

This retrospective, single-center cohort study was approved by the local ethics and institutional review board of Tokyo Women's Medical University (TWMU), Tokyo, Japan (approval number: 5511). The requirement for informed consent was waived by the ethical review board. We guaranteed an opt-out opportunity on the homepage of the TWMU.

Consecutive patients who underwent transfemoral transcatheter aortic valve implantation (TF-TAVI) under general anesthesia at TWMU between January 2018 and May 2019 were enrolled. To investigate the influence of the type of prosthetic valve and hemodynamic changes on cerebral rSO₂, the patients were divided into three groups: group A, B, and C. Group A received a balloon-expandable valve and recovered their systolic blood pressure to 90 mmHg within 45 s after valve deployment. Group B received a balloon-expandable valve but recovered their systolic blood pressure more than 45 s after valve deployment. Group C received a self-expandable valve and almost immediately recovered their systolic blood pressure to 90 mmHg during valve deployment.

2.2 Cerebral rSO₂ measurement

We used a O3™ regional oximetry device (Masimo Corporation, Irvine, CA, USA) to measure cerebral rSO₂. O3™ sensors were applied to both right and left sides of the forehead, and cerebral rSO₂ values were continuously recorded every 2 s. Cerebral rSO₂ values were retrospectively analyzed at five time points: pre-induction (baseline), start of the procedure, start of valve deployment, lowest cerebral rSO₂ value related to valve deployment, and end of the procedure. Pre-induction baseline cerebral rSO₂ values were obtained before pre-oxygenation to induce general anesthesia. Intraoperative vital data during TAVI were recorded continuously in graphical and numerical formats and stored in a database. We used the cerebral rSO₂ values obtained from the left side of the forehead because over 50% of the data from the right side were lost in two of the study participants, while the data

from the left side were recorded more successively and stably. The relationships among left side cerebral rSO₂ values, preoperative blood examination variables, and physical and hemodynamic characteristics were then investigated.

2.3 Anesthetic management

General anesthesia was induced with midazolam, fentanyl, remifentanyl, and rocuronium administered after insertion of a radial arterial line. A balanced anesthetic technique including fentanyl, remifentanyl, rocuronium, and sevoflurane or desflurane was used to maintain anesthesia. In patients with ventricular dysfunction, a central line was inserted. Invasive arterial blood pressure and transesophageal echocardiography were recorded under standard general anesthesia monitoring.

2.4 Statistical analysis

We investigated the association of intraoperative cerebral rSO₂ values in the TAVI procedure with different variables, namely blood analysis data, TTE variables, STS risk of mortality, STS morbidity or mortality, EURO SCORE II, and hemodynamic changes related to valve deployment under general anesthesia. Given that most of the relevant data were not normally distributed after performing the Shapiro-Wilk test, all data, if not stated otherwise, were presented as medians [25–75% quartiles]. Between-group comparisons were performed using Pearson's chi-square test for categorical variables and the Wilcoxon rank-sum test or Kruskal-Wallis test, as appropriate, for continuous variables. Spearman's coefficient (ρ) was used to characterize relationships between continuous variables. Receiver operating characteristic (ROC) analysis was used to determine the optimal cutoff point for the nadir of cerebral rSO₂ values during valve deployment that predicted prolonged hypertension. All statistical analyses were performed using JMP® Pro version 16.0.0 (SAS Institute Inc., Cary, NC, USA). Differences were considered statistically significant at $p < 0.05$.

3 Results

Overall, 117 consecutive patients who underwent TF-TAVI under general anesthesia were enrolled in the study. The real-time vital data were missing for 3 patients, and cerebral rSO₂ was not recorded in 23 patients. Finally, the data of 91 patients (26 (28.6%) males) aged 69–92 years were analyzed; among them, 60 and 31 patients had a balloon-expandable valve and self-expandable valve, respectively. Table 1 shows the patient characteristics and preoperative

Table 1 Clinicodemographic patient characteristics

Variable	Median [IQR1-IQR3]	Number of patients with missing data
Patient characteristics		
Age (years)	83 [80–87]	
Males/females	26 (28.6%)/65 (71.4%)	
Height (cm)	149 [142.2–157.0]	
Weight (kg)	45.8 [40.8–55.2]	
BSA (m ²)	1.40 [1.28–1.55]	
STS risk of mortality (%)	4.9 [3.8–6.8]	
STS morbidity or mortality (%)	19.2 [14.5–26.7]	
EURO SCORE II risk of in-hospital mortality (%)	3.8 [2.5–6.0]	
Preoperative laboratory data		
Hemoglobin (g/dL)	11.2 [10.4–12]	
Creatinine (mg/dL)	0.93 [0.7–1.16]	
eGFR (mL/min/1.73m ²)	47.2 [35.6–64]	
Na (mEq/L)	140 [138–141]	
K (mEq/L)	4.3 [4.1–4.7]	
Cl (mEq/L)	104 [102–106]	
TSH (μIU/mL)	2.4 [1.3–4.2]	1
ft3 (pg/mL)	2.4 [2.1–2.7]	1
ft4 (ng/dL)	1.3 [1.2–1.4]	1
BNP (pg/mL)	207 [100.8–495.0]	2
Preoperative TTE data		
FS	0.3 [0.26–0.35]	
EF (%)	57 [50–59]	
LV mass (g)	159 [123–207]	
LVMI (g/m ²)	110 [92–142]	
LVDd (cm)	4.4 [4.1–5]	
LVDs (cm)	3 [2.7–3.5]	
IVST (cm)	1 [0.9–1.2]	
LAVI (g/m ²)	55.8 [35.9–74.8]	4
PWT (cm)	1 [0.9–1.2]	
AV peak velocity (m/s)	4.1 [3.6–4.7]	
TR max velocity (m/s)	2.6 [2.3–3]	6
RVSP (mmHg)	37 [31.2–46]	6
E/e*	19.5 [14.4–25.4]	14
s*(sep) (cm/s)	5.2 [4.3–5.8]	13
e*(sep) (cm/s)	4 [3.4–5]	12
AVA (continuous) (cm ²)	0.70 [0.54–0.86]	3
AVA index (cm ² /m ²)	0.49 [0.38–0.6]	

IQR, interquartile range; BSA, body surface area; STS, Society of Thoracic Surgeons; eGFR, estimated glomerular filtration rate; TSH, thyroid stimulating hormone; ft3, free triiodothyronine; ft4, free thyroxine; BNP, B-type natriuretic peptide; FS, fractional shortening; EF, ejection fraction; LV, left ventricle; LVMI, left ventricular mass index; LVDd, left ventricular diastolic diameter; LVDs, left ventricular systolic diameter; IVST, interventricular septum thickness; LAVI, left atrial volume index; PWT, posterior wall thickness; AV, aortic valve; TR, tricuspid regurgitation; RVSP, right ventricular systolic pressure; E/e*, ratio of early mitral inflow velocity to mitral annular tissue Doppler early diastolic velocity; s*, mitral annular tissue Doppler systolic myocardial velocity; sep, septal; AVA, aortic valve area

clinical variables. Data were missing for some clinical variables in a number of patients. The preoperative clinical variables revealed high brain natriuretic peptide (BNP) (207 [100.8–495.0] pg/mL), low hemoglobin (11.2 [10.4–12] g/dL), high left ventricular mass index (LVMI; 110 [92–142] g/m²), preserved left ventricular ejection fraction (EF; 57% [50–59%]), and small aortic valve area (AVA) index (0.49 [0.38–0.6] cm²/m²).

We observed significant differences in cerebral rSO₂ values between hemispheres at baseline (left, *n*=91: 58 [54–63] vs. right, *n*=89: 60 [56–64], *p*=0.0041), the start of the procedure (left, *n*=91: 59 [55–65] vs. right, *n*=89:

61 [56–65], *p*=0.024), and the end of the procedure (left, *n*=91: 59 [55–64] vs. right, *n*=89: 61 [57–64], *p*=0.039). However, no statistical difference was observed at the start of valve deployment (left, *n*=91: 60 [54–64] vs. right, *n*=89: 60 [55–64], *p*=0.7098) and the lowest cerebral rSO₂ (left, *n*=91: 48 [44–54] vs. right, *n*=89: 50 [44–54.5], *p*=0.1872). It is worth noting that two participants lost over 50% of the data from the right side cerebral rSO₂ values, probably due to device or probe problem. Furthermore, cerebral rSO₂ values obtained from the left side of the forehead were more successive and stable than those obtained from the right side.

The baseline cerebral rSO₂ was associated with preoperative BNP ($r=-0.52$, $p<0.0001$), hemoglobin ($r=0.33$, $p=0.0016$), fractional shortening (FS; $r=0.37$, $p=0.0003$), EF ($r=0.32$, $p=0.0021$), LVMI ($r=-0.33$, $p=0.0013$), left ventricular diastolic diameter (LVD; $r=-0.36$, $p=0.0005$),

Table 2 Association between baseline cerebral regional oxygen saturation (rSO₂) and clinical variables

Clinical variable	Spearman's coefficient	Significance (p)
Patient characteristics		
STS risk of mortality (%)	-0.35	$p=0.0007$
STS morbidity or mortality (%)	-0.40	$p<0.0001$
EURO SCORE II risk of in-hospital mortality (%)	-0.29	$p=0.0058$
Preoperative laboratory data		
Hemoglobin (g/dL)	0.33	$p=0.002$
Creatinine (mg/dL)	-0.21	$p=0.049$
eGFR (mL/min/1.73 m ²)	0.19	$p=0.079$
Na (mEq/L)	0.17	$p=0.116$
K (mEq/L)	-0.07	$p=0.528$
Cl (mEq/L)	0.10	$p=0.324$
TSH (μIU/mL)	-0.02	$p=0.883$
fT3 (pg/mL)	0.17	$p=0.100$
fT4 (ng/dL)	-0.08	$p=0.439$
BNP (pg/mL)	-0.52	$p<0.0001$
Preoperative TTE data		
FS	0.37	$p=0.0003$
EF (%)	0.32	$p=0.0021$
LV mass (g)	-0.27	$p=0.0092$
LVMI (g/m ²)	-0.33	$p=0.0013$
LVDd (cm)	-0.29	$p=0.0046$
LVDs (cm)	-0.36	$p=0.0005$
IVST (cm)	-0.10	$p=0.3265$
LAVI (g/m ²)	-0.22	$p=0.0431$
PWT (cm)	-0.14	$p=0.2012$
AV peak velocity (m/s)	-0.03	$p=0.7863$
TR max velocity (m/s)	-0.14	$p=0.1885$
RVSP (mmHg)	-0.14	$p=0.1885$
E/e*	-0.09	$p=0.4364$
s*(sep) (cm/s)	0.29	$p=0.0110$
e*(sep) (cm/s)	0.09	$p=0.4527$
AVA (continuous) (cm ²)	0.15	$p=0.1772$
AVA index (cm ² /m ²)	0.13	$p=0.2304$

STS, Society of Thoracic Surgeons; eGFR, estimated glomerular filtration rate; TSH, thyroid stimulating hormone; fT3, free triiodothyronine; fT4, free thyroxine; BNP, B-type natriuretic peptide; FS, fractional shortening; EF, ejection fraction; LV, left ventricle; LVMI, left ventricular mass index; LVDd, left ventricular diastolic diameter; LVDs, left ventricular systolic diameter; IVST, interventricular septum thickness; LAVI, left atrial volume index; PWT, posterior wall thickness; AV, aortic valve; TR, tricuspid regurgitation; RVSP, right ventricular systolic pressure; E/e*, ratio of early mitral inflow velocity to mitral annular tissue Doppler early diastolic velocity; s*, mitral annular tissue Doppler systolic myocardial velocity; sep, septal; AVA, aortic valve area

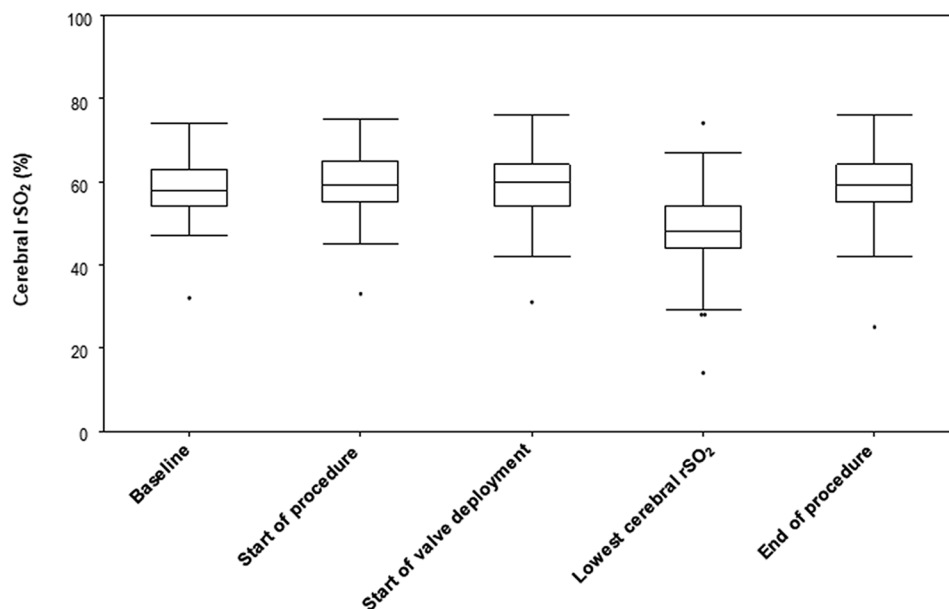
STS risk of mortality ($r=-0.35$, $p=0.0007$), and STS morbidity or mortality ($r=-0.40$, $p<0.0001$; Table 2). Figure 1 shows the changes in the cerebral rSO₂ values at five time points during TAVI. The lowest cerebral rSO₂ value was 48 [44–54], and it was associated with valve deployment. Further, this was significantly lower than the cerebral rSO₂ values at baseline (58 [54–63]), start of the procedure (59 [55–65]), start of valve deployment (60 [54–64]), and end of the procedure (59 [55–64]) (all $p<0.0001$). Meanwhile, there were no significant differences in the cerebral rSO₂ values among the other time points.

Groups A and B involved 30 patients each. Group C involved 31 patients. There were no conversions to open surgery, although the following complications occurred: postoperative pacemaker implantation in 3 patients (group B, 1 patient; group C, 2 patient); vascular injury in 2 patients (group C); pericardial effusion in 1 patient (group B); symptomatic cerebral infarction in 1 patient (group C); and coronary occlusion in 1 patient (group C). There were no significant differences in the clinical variables of patient characteristics, preoperative laboratory data, and preoperative TTE data among the three groups except for differences in potassium concentration (4.3 [3.9–4.5] in group A vs. 4.5 [4.2–4.9] in group B vs. 4.4 [4.3–4.8] in group C, $p=0.0313$) and LAVI (41.8 [32.9–63.6], $n=28$ in group A vs. 55.3 [39.3–77.9], $n=29$ in group B vs. 60.9 [43.8–79.8], $n=30$ in group C, $p=0.0432$; Table 3). Table 4 shows the cerebral rSO₂ values at the five time points and the rate of decrease from baseline or at the start of valve deployment to the lowest cerebral rSO₂ in the three groups. There were no significant differences among the three groups at the five time points, except for the lowest cerebral rSO₂ related to valve deployment. Group B showed the lowest cerebral rSO₂ values (45 [38.8–48.3]) related to valve deployment (group A (47.5 [44.8–51]); group C (55 [48–61]), $p<0.0001$). Additionally, the difference in cerebral rSO₂ from the start of valve deployment to the lowest cerebral rSO₂ value was -19.7% [14.6–23.7%] in group A, -20.1% [16.7–28.9%] in group B, and -13.7% [5.7–18.6%] in group C. The cerebral rSO₂ in group B was significantly lower than that in groups A and C ($p<0.0001$; Fig. 2). ROC analysis of the lowest cerebral rSO₂ values associated with valve deployment and prolonged hypotension in >45 s showed that the optimal cut-off value was 46%, with an AUC of 0.736, sensitivity of 67%, specificity of 69%, and a p value of 0.0003 (Fig. 3).

4 Discussion

The relationship of cerebral rSO₂ values with preoperative clinical variables and prolonged hypotension related to valve deployment has not been established to date. This

Fig. 1 Overall intraoperative evolution of cerebral regional oxygen saturation (rSO₂) values in the five time points



study found that baseline cerebral rSO₂ was associated with preoperative BNP, hemoglobin, FS, EF, LVMI, LVDs, STS risk of mortality, and STS morbidity or mortality. Moreover, patients who took longer to recover their systolic blood pressure to 90 mmHg after valve deployment with a balloon-expandable valve (Group B) had the lowest cerebral rSO₂ values during deployment. This suggests that severe decline in cerebral rSO₂ during valve deployment may predict prolonged hypotension.

The mean baseline bihemispheric rSO₂ value (56%) in this study was significantly lower than that reported in healthy adults [15]. In a previous study on healthy adults, the mean cerebral rSO₂ value measured by O3™ regional oximetry was approximately 68%, with narrow confidence intervals of 1% (age 35 ± 9.9 years old). The low baseline cerebral rSO₂ values recorded in our study may have been influenced by the characteristics of our study participants, who were frail and elderly (83.2 ± 4.9 years) with serious symptomatic AS. This may have resulted in brain atrophy, poor left ventricular function, heart failure, and anemia [16]. Moreover, we observed a significant difference in the baseline cerebral rSO₂ values between the right and left parts of the forehead. However, the clinical significance of this difference is unknown. Similarly, in the previous study involving healthy adults, there was a significant yet quantitatively small difference between cerebral rSO₂ values of the right and left hemispheres [15]. The difference between the left and right parts of the forehead may have been influenced by the varying characteristics of the NIRS devices from different manufacturers. These characteristics included wavelength, number of wavelengths, sensor configuration, and propriety integrated algorithms used to determine

tissue saturation values [1–3]. Another possible reason is that the thickness of the skull bone and cerebrospinal fluid layer affect the measurement of cerebral rSO₂ [2]. Old frail patients who undergo TAVI may have significant brain atrophy. Therefore, the different distance from the emitter and detector due to unequal brain atrophy would influence the amount of near-infrared light returns to the detector and result in the difference of in the forehead rSO₂ between the left and right sides.

The current results showed that the baseline cerebral rSO₂ values were associated with BNP, hemoglobin, left ventricular function, left ventricular hypertrophy, and the STS risk score. The preoperative laboratory analyses revealed high BNP and low hemoglobin levels. This suggested that patients who undergo TAVI experience congestive heart failure and were likely to develop hemodynamic instability [17]. Low baseline rSO₂ values associated with BNP values may be useful in identifying patients at a high risk of adverse events. Additionally, the association between baseline cerebral rSO₂ and left ventricular function suggests that good left ventricular function maintains cardiac output, resulting in preserved cerebral perfusion that influences the cerebral rSO₂. Overall, the cerebral rSO₂ values measured using O3™ regional oximetry are related to cardiac failure and function. TAVI is associated with transient hypotension due to valve deployment. However, hypotension sometimes persists and requires aggressive medical interventions. It is clinically challenging to establish the optimal cut-off value of cerebral rSO₂ that is predictive of prolonged hypotension. This study found that patients who received a balloon-expanding valve but did not recover from shock within 45s (group B) had the lowest cerebral rSO₂ value related to

Table 3 Comparison between patient characteristics and preoperative clinical variables among groups A, B, and C

	Group A	Group B	Group C	Significance
Patient characteristics				
Patient number, N	30	30	31	$p=0.9891$
Males/females, N (%)	11 (36.7) / 19 (63.3)	9 (30) / 21 (70)	6 (19.4) / 25 (80.6)	$p=0.3192$
Age (years)	83.0 [80.0–86.0]	82.5 [78.8–89.0]	84.0 [80.0–87.0]	$p=0.9627$
Height (cm)	149.1 [142.1–162.6]	149.0 [142.8–156.1]	149.0 [142.0–157.0]	$p=0.9119$
Weight (kg)	47.7 [40.7–58.8]	46.3 [42.1–58.2]	44.7 [40.3–52.7]	$p=0.6313$
BSA (m ²)	1.39 [1.23–1.60]	1.43 [1.29–1.58]	1.39 [1.28–1.50]	$p=0.6875$
STS risk of mortality (%)	4.8 [3.6–6.3]	4.7 [3.2–6.4]	6.4 [4.5–8.6]	$p=0.0794$
STS morbidity or mortality (%)	19.1 [13.9–28.6]	19.2 [12.7–24.3]	18.8 [15.4–32.4]	$p=0.3874$
EURO SCORE II risk of in-hospital mortality (%)	3.5 [2.4–4.6]	4.0 [2.5–5.9]	4.6 [2.9–9.2]	$p=0.1589$
Preoperative laboratory data				
Hemoglobin (g/dL)	11.3 [10.4–11.8]	11.2 [10.1–12.1]	11.1 [10.6–12]	$p=0.9854$
Creatinine (mg/dL)	1.0 [0.7–1.6]	0.9 [0.8–1.1]	0.8 [0.7–1.1]	$p=0.4490$
eGFR (mL/min/1.73 m ²)	43.2 [29.4–61.1]	48.8 [41.7–65.0]	48.7 [35.7–64]	$p=0.4957$
Na (mEq/L)	140.5 [139–141.3]	139.5 [137.8–142]	140 [138–141]	$p=0.3786$
K (mEq/L)	4.3 [3.9–4.5]	4.5 [4.2–4.9]	4.4 [4.3–4.8]	$p=0.0313$
Cl (mEq/L)	104 [102–106.3]	103 [99.8–106]	104 [102–106]	$p=0.6389$
TSH (μIU/mL)	3.1 [2.0–4.3]	1.8 [1.0–3.1]	2.4 [1.6–4.9]	$p=0.0773$
ft3 (pg/mL)	2.4 [1.9–2.6]	2.5 [2.2–2.6]	2.4 [2.1–2.8]	$p=0.6042$
ft4 (ng/dL)	1.2 [1.1–1.4]	1.3 [1.2–1.4]	1.2 [1.1–1.5]	$p=0.2734$
BNP (pg/mL)	192.2 [75–490.2]	180.7 [111.2–327.9]	257.9 [101–625.7]	$p=0.6436$
Preoperative TTE data				
FS	0.29 [0.25–0.34]	0.3 [0.28–0.35]	0.3 [0.25–0.35]	$p=0.8735$
EF (%)	57.0 [50.3–59.3]	56.4 [50.0–58.3]	55 [50–60]	$p=0.9768$
LV mass (g)	164 [115.8–235.8]	155.5 [118.5–189.8]	159 [128–182]	$p=0.650$
LVMI (g/m ²)	118 [91–148]	103.5 [80.5–139.8]	115 [95–124]	$p=0.7020$
LVDd (cm)	4.45 [4.4–83]	4.45 [4.1–4.83]	4.4 [4.1–5.1]	$p=0.8241$
LVDs (cm)	3.05 [2.70–3.45]	3.00 [2.70–3.30]	3.00 [2.60–3.80]	$p=0.9093$
IVST (cm)	1.1 [0.9–1.2]	1.0 [0.8–1.2]	1.0 [0.9–1.2]	$p=0.5741$
LAVI (g/m ²)	41.8 [32.9–63.6] ($N=29$)	55.3 [39.3–77.9] ($N=29$)	60.9 [43.8–79.8] ($N=30$)	$p=0.0432$
PWT (cm)	1.1 [0.9–1.2]	1.0 [0.8–1.2]	1.0 [0.9–1.1]	$p=0.5895$
AV peak velocity (m/s)	4.2 [3.7–4.6]	4.1 [3.6–4.3]	4.1 [3.8–4.9]	$p=0.2404$
AVA (continuous or planimetry) (cm ²)	0.71 [0.59–0.88]	0.73 [0.58–0.87]	0.68 [0.48–0.83]	$p=0.5660$
AVA index (cm ² /m ²)	0.52 [0.38–0.59]	0.50 [0.42–0.60]	0.47 [0.32–0.60]	$p=0.7344$
TR max velocity (m/s)	2.6 [2.2–3.0] ($N=29$)	2.6 [2.3–2.8] ($N=28$)	2.8 [2.4–3.2] ($N=28$)	$p=0.2318$
RVSP (mmHg)	37 [31.7–40.9] ($N=29$)	37 [31.7–40.9] ($N=28$)	40.3 [33.5–51] ($N=28$)	$p=0.2318$
E/e* (sep)	16.5 [14.5–23.5] ($N=28$)	19.8 [13.9–23.7] ($N=27$)	21.3 [14.3–34.1] ($N=22$)	$p=0.3500$
s* (sep) (cm/s)	5.3 [5.0–5.6] ($N=27$)	4.9 [3.9–5.9] ($N=26$)	5.2 [4.3–6.0] ($N=25$)	$p=0.2472$
e* (sep) (cm/s)	3.9 [3.4–4.8] ($N=27$)	4.5 [3.4–5.8] ($N=27$)	4 [3.4–5.7] ($N=25$)	$p=0.4049$
E (cm/s)	74 [58.3–89.2] ($N=29$)	77.9 [58.9–105.9] ($N=24$)	87.4 [61.7–142.7] ($N=19$)	$p=0.3145$

Table 3 (continued)

	Group A	Group B	Group C	Significance
A (cm/s)	101 [79.2–121] (N=27)	99.4 [84.1–115] (N=17)	101 [79.8–117.5] (N=17)	<i>p</i> =0.9477
E/A	0.7 [0.6–1.0] (N=27)	0.7 [0.6–1.0] (N=17)	0.9 [0.6–1.4] (N=16)	<i>p</i> =0.2961

Group A, patients in balloon-expandable valve who recovered their systolic blood pressure to 90 mmHg within 45 s after valve deployment; group B, patients in balloon-expandable valve who took more than 45 s to recover from hypotension; group C, patients who received self-expandable valves

N, patient number; BSA, body surface area; STS, Society of Thoracic Surgeons; eGFR, estimated glomerular filtration rate; TSH, thyroid stimulating hormone; fT3, free triiodothyronine; fT4, free thyroxine; BNP, B-type natriuretic peptide; FS, fractional shortening; EF, ejection fraction; LV, left ventricle; LVMI, left ventricular mass index; LVDD, left ventricular diastolic diameter; LVDs, left ventricular systolic diameter; IVST, interventricular septum thickness; LAVI, left atrial volume index; PWT, posterior wall thickness; AV, aortic valve; AVA, aortic valve area; TR, tricuspid regurgitation; RVSP, right ventricular systolic pressure; E/e*, ratio of early mitral inflow velocity to mitral annular tissue Doppler early diastolic velocity; s*, mitral annular tissue Doppler systolic myocardial velocity; sep, septal; E, early diastolic filling velocity; A, atrial filling velocity

Table 4 Cerebral regional oxygen saturation (rSO₂) values at five time points and decrease rate from baseline or start of valve deployment to the lowest cerebral rSO₂ among the three groups

Time point / decrease rate of cerebral rSO ₂	Group A	Group B	Group C	Significance
Baseline	59 [54.8–63.3]	57.5 [53.5–61.3]	56 [52–64]	<i>p</i> =0.4772
Start of procedure	61 [58–64.3]	57.5 [54–64]	58 [55–68]	<i>p</i> =0.2007
Start of valve deployment	60 [57.5–62]	56.5 [52–63.3]	62 [56–68]	<i>p</i> =0.0639
Lowest cerebral rSO ₂	47.5 [44.8–51]	45 [38.8–48.3]	55 [48–61]	<i>p</i> <0.0001
End of procedure	61.5 [56.5–64.5]	59 [54–65.3]	59 [53–66]	<i>p</i> =0.6199
Decrease rate from start of valve deployment to the lowest cerebral rSO ₂ (%)	19.7 [14.6–23.7]	20.1 [16.7–28.9]	13.7 [5.7–18.6]	<i>p</i> <0.0001
Decrease rate from baseline to the lowest cerebral rSO ₂ (%)	19.1 [13.4–23.4]	22.5 [17.5–30.0]	8.7 [-1.8–13.7]	<i>p</i> =0.0001

Fig. 2 Percentage change from start of valve deployment to the lowest cerebral rSO₂, rSO₂, regional oxygen saturation

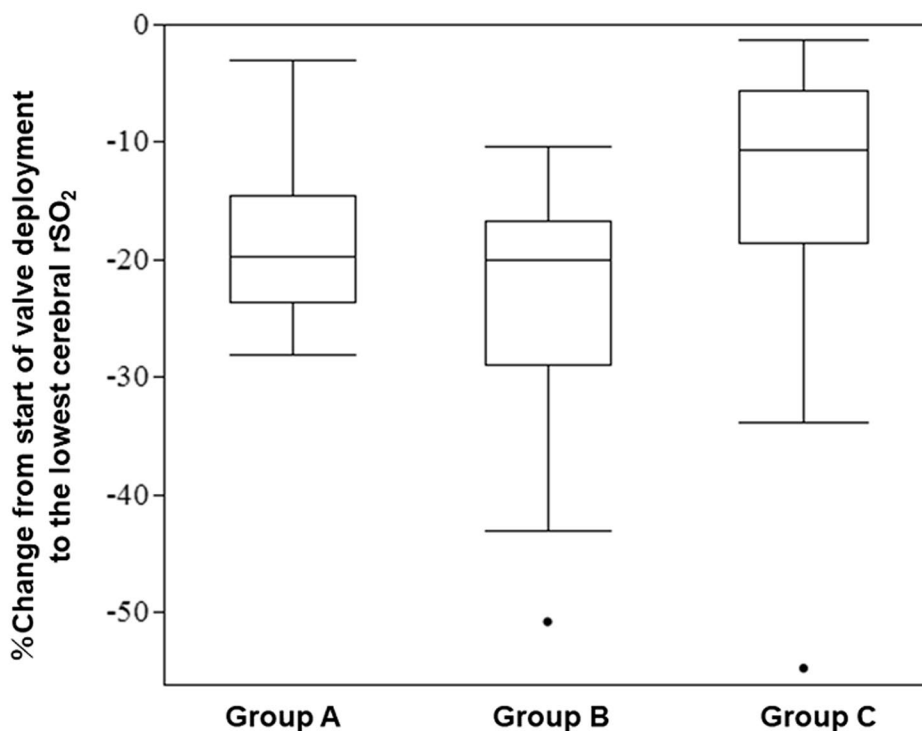
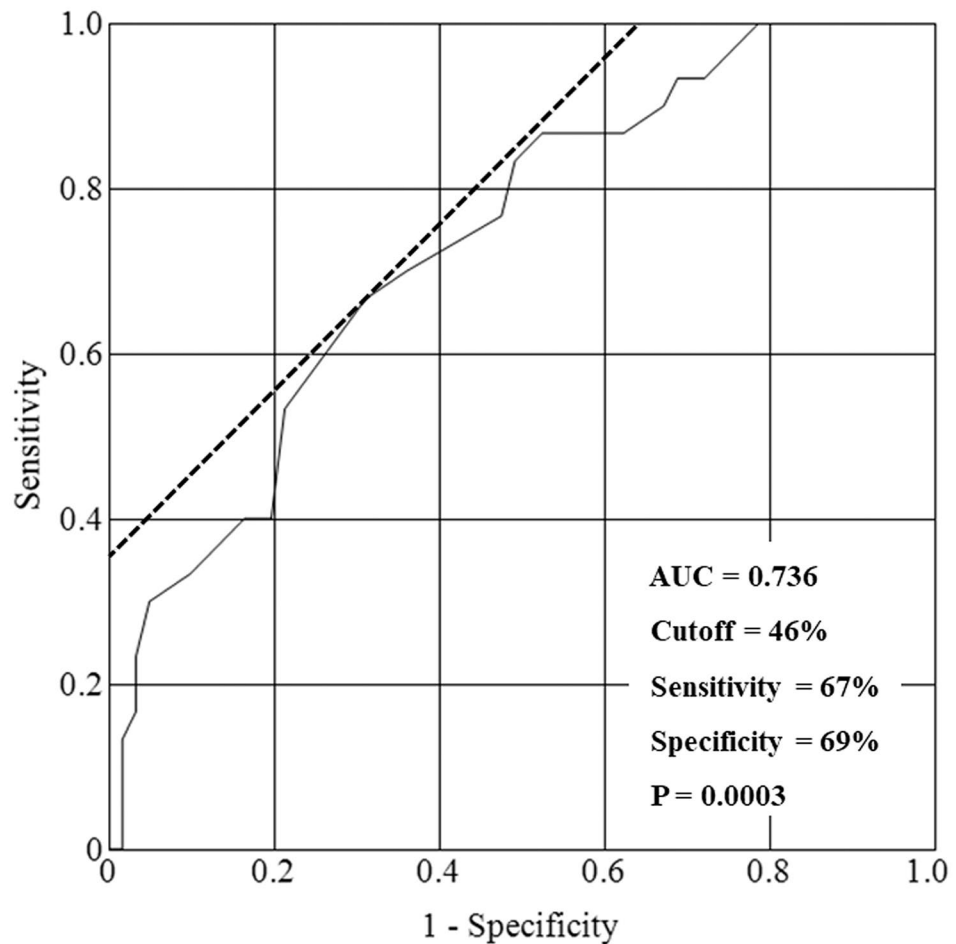


Fig. 3 Receiver operating characteristic analysis for the lowest cerebral rSO₂ values associated with valve deployment and persist hypotension. rSO₂, regional oxygen saturation; AUC, area under the curve



valve deployment, with their values significantly lower than those of patients with faster recovery with balloon-expandable valve (group A) and with self-expandable valve (group C). This result may be related to the fact that patients who experience cardiac arrest with lower cerebral rSO₂ require a longer time to achieve return of spontaneous circulation [4, 5]. Thus, a severe decrease in cerebral rSO₂ may predict prolonged hypotension after valve deployment in TAVI.

These findings suggest that it is important to maintain high cerebral rSO₂ values at the onset of valve deployment and minimize the decline in cerebral rSO₂ during this process. While aggressive interventions to improve cerebral rSO₂ values, such as transfusions, and inotropic and vasopressor infusions, are known to increase cerebral blood flow, perfusion pressure, blood oxygen content, and cardiac output [13], evidence is limited regarding their impact on postoperative neurological outcomes and cognitive dysfunction [18, 19].

In our study, a cerebral rSO₂ value of <46% predicted hypotension lasting more than 45 s; therefore, the cerebral rSO₂ value should probably be maintained at least 46%. Low baseline cerebral rSO₂ values were associated with

preoperative clinical variables related to cardiac failure and low cardiac systolic function.

We found an association between declined cerebral rSO₂ and prolonged hypotension after valve deployment in TAVI and identified a cut-off value. The cerebral rSO₂ data obtained from this study can be helpful in providing early management and improve the outcomes of TAVI. However, this study also had several limitations. First, it was a retrospective study with a small sample size. Second, only the cerebral rSO₂ values obtained from the left side were analyzed because over 50% of the data on the right side were lost in two patients. Moreover, there were significant differences in baseline cerebral rSO₂ values between the left and right hemispheres, but we did not consider the influence of this difference. Third, the preoperative TTE records used to estimate diastolic function had missing data. Thus, we could not examine the relationship between cerebral rSO₂ and diastolic function satisfactorily. Further prospective studies are necessary to confirm our findings and identify older patients who require further aggressive clinical interventions to avoid prolonged hypotension in the setting of TAVI.

5 Conclusion

Baseline cerebral rSO₂ values measured using O3™ regional oximetry are associated with preoperative BNP, hemoglobin levels, left ventricular function, and STS risk scores in patients who undergo TAVI. Additionally, the balloon-expandable valve group, in which systolic blood pressure takes over 45 s to recover after valve deployment, shows a significant decline in cerebral rSO₂. Importantly, a severe decline in cerebral rSO₂ associated with valve deployment may be a predictive factor for prolonged hypotension during TAVI. Moreover, a cerebral rSO₂ cutoff value of 46% predicted delayed recovery from hypotension within 45 s. Therefore, it is recommended to maintain the cerebral rSO₂ value at or above 46% during TAVI.

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Author contributions SI conducted the study, collected and analyzed the data, and prepared the manuscript. MO supported data analysis and manuscript preparation.

Declarations

Ethical approval Cerebral rSO₂ values were obtained from anesthetized patients with ethical approval (No. 5511) from the Institutional Review Board of Tokyo Women's Medical University Hospital.

Consent to participate and for publication For this non-interventional and noninvasive retrospective observational study, the requirement for informed patient consent was waived by the IRB of TWMU. Patients were provided with an opt-out option, of which they were notified on the homepage of the TWMU.

Competing interests The authors declare no competing interests.

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