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Comparative Study of Noninvasive Cerebrovascular Monitoring Methods in Cardiac Surgery

Kazuhiro KOCHI, Kazumasa ORIHASHI and Taijiro SUEDA
First Department of Surgery, Hiroshima University School of Medicine, Hiroshima, Japan

ABSTRACT

Unfavorable incidents during cardiac operations due to inadequate cerebral perfusion can be avoided by the utilization of noninvasive blood flow monitoring methods. The purpose of this study was to evaluate monitoring systems for cebrovascular perfusion. We compared currently available blood flow monitoring devices including transcranial Doppler (TCD), central retinal artery color Doppler (CRAD) and near-infrared spectroscopy (NIRS). The maximum flow velocity (Vmax) of the right central retinal artery was measured with a 7.5 MHz Doppler system. The Vmax of the right middle cerebral artery was measured with a TCD system. Regional tissue oxygen saturation (rSO_2) was continuously measured with a NIRS system. The total number of individual data for each monitoring method collected from 25 patients was 184. The CRAD-Vmax was correlated more closely with the corresponding maximum blood pressure than the TCD-Vmax (r = 0.742 and 0.607, respectively). No missing data were seen in CRAD, but 20 missing data were seen in TCD, mostly during the period of cardiopulmonary bypass with lowered blood pressure. All 184 data were divided into two groups: Group 1 ($rSO_2 \geq 60$ %, n=175) and Group 2 ($rSO_2 < 60$ %, n=9 data). The CRAD-Vmax was significantly lower in Group 2 (5.2 ± 2.4 cm/s versus 3.0 ± 0.4 cm/s, $p<0.001$). However, there was no significant difference in the TCD-Vmax between these two groups. Thus, CRAD may be superior to TCD in detecting insufficiency of cerebral blood flow correlating to rSO_2, and could be used as the first choice monitoring system of cerebral blood flow during cardiac surgery.

Key words: *Doppler ultrasound, Stroke Prevention, Monitor in Cardiac Surgery*

Stroke during cardiac surgery is caused either by an occurrence of embolism or by sustained malperfusion of the brain[20,22]. In order to avoid the former, prevention is of primary importance because it is practically unfeasible to detect every embolus and remove it immediately in the operating theatre[3,19]. In contrast, the latter may be solved by means of pharmacological intervention or mechanical support, if it is detected and adequate perfusion is restored without delay. For this purpose, an accurate monitoring modality available in the operative theater is essential. However, some limitations are present in the clinical setting: 1) space and time in the operating theatre which limits the use of theoretically ideal monitoring devices, such as scintigraphy or magnetic resonance imaging, and 2) the skull which limits access to the brain. A few modalities are practically available at present.

Transcranial Doppler (TCD) has been utilized to measure the blood flow velocity in the intracranial arteries for years. In spite of its advantages that real-time information can be provided noninvasively, technical difficulties have been pointed out by several investigators, including poor insonation of the temporal window and poor detection of Doppler signals under low perfusion pressure[6,12,21].

Thus, we have sought another modality and recently developed central retinal artery color Doppler (CRAD)[14,15]. Since the target artery of CRAD is different from that of TCD, a correlation between the CRAD- and TCD-data was examined in a previous study. There was a good correlation between the two sets of Doppler-derived data when they were normalized (not absolute values)[10].

We have also introduced near-infrared spectroscopy (NIRS), which is capable of providing information on oxygen balance in the brain tissue by measuring the regional oxygen saturation (rSO_2) of brain tissue. However, we have recognized that NIRS data change differently from

Address reprint requests to Dr.Kazuhiro Kochi, First Department of Surgery, Hiroshima University School of Medicine, 1–2–3 Kasumi, Minami-ku, Hiroshima, 734–8551, Japan
TEL: Int-81-82-2575218, FAX: Int-81-82-2575219
E-mail: userdrkk@aol.com

Doppler-derived data. To date, no comparative study of the Doppler systems has been available.

The purpose of this study is: 1) to examine the correlation between the TCD- and CRAD-data (absolute values) collected simultaneously in order to evaluate CRAD as a possible substitute for TCD; 2) to clarify the advantages of CRAD in comparison with TCD; and 3) to correlate the NIRS data with the Doppler data.

PATIENTS AND METHODS

Patients and clinical management

This study was approved by the Ethical Committee of our institution and informed consent was obtained from every patient. We examined consecutively twenty five patients who underwent cardiac surgery using cardiopulmonary bypass (CPB) and had no preoperative history of stroke. They included 17 men and 8 women with ages ranging from 16 to 79 years (average 61.5 years). The operative procedures were coronary artery bypass grafting, valve replacement, and closure of an atrial septal defect in 10, 12, and 3 patients, respectively. Every patient was operated upon by a single surgeon during this period.

Induction and maintenance of anesthesia was carried out under the same protocol with high dose fentanyl and propofol. During CPB, the arterial pH was maintained at 7.4 and the pCO_2 was regulated between 35 to 40 mmHg by adjusting the gas flow rate of the oxygenator. The target flow rate was 2.6 L/min/m^2. The minimal rectal temperature was 33 degrees centigrade. When the hemoglobin concentration was lower than 7 g/dl, blood transfusion was performed.

Protocol for data collection

In every case, the maximum flow velocity (Vmax; cm/sec) in the right middle cerebral artery (TCD) and the right central retinal artery (CRAD), the maximum blood pressure (BPmax; mmHg), and the rSO_2 (NIRS) of the right frontal lobe were simultaneously measured as one data set. Data were collected principally at 7 preset stages of the operation: 1) before CPB, 2) on CPB, 3) during cooling, 4) under total CPB, 5) during rewarming, 6) during weaning from CPB, and 7) after CPB. Data were additionally collected whenever the blood pressure changed by more than 30 mmHg in a minute.

TCD was performed by a single experienced examiner (the first author) according to the method previously reported, using a 2 MHz TCD system (TC2-64B Doppler Ultrasound Velocimeter, EME Co., Uberlingen, Germany). The right side temporal window was scanned just above the zygomatic arch. The orientation and depth of the middle cerebral artery was adjusted to obtain the best possible Doppler signal strength[8,10,14].

The CRAD technique was as previously reported[1,10,14]. The right eye was scanned horizontally through an adhesive patch by using a 7.5 MHz sector probe of an echocardiographic system (EUP-S33, EUB-555, Hitachi Medical Co. Inc., Tokyo, Japan). The ultrasonic power was set to the lowest level to minimize possible damage to the ocular tissues. The central retinal artery was visualized with its course as parallel to the ultrasonic beam as possible. The sampling volume of 1 mm in length was placed on the central retinal artery 2 mm away from the optic disc.

A NIRS probe with a distance of 40 mm between the emitter and receiver was placed on the forehead at induction of anesthesia, and rSO_2 in the right frontal lobe 2 cm deep from the skin was continuously monitored by means of a NIRS system, TOS-96 (TOSTEC Co., Tokyo, Japan). The data were saved as a text file in the hard disc of this system.

To enable a simultaneous recording of the TCD-, CRAD-, and blood pressure data, output signals from the TCD system and echo system together with video images of arterial blood pressure monitor and operative field were displayed on a single screen by dividing it into four parts using a screen edit (Quard screen unit, VQ402, Takenaka Engineering Co. Ltd., Kyoto, Japan). The edited images were recorded on S-VHS tapes with a videocassette recorder (AG-7300, Panasonic, Osaka, Japan) for later analysis.

Data analysis

The Vmax value was expressed as an average of 10 consecutive beats of Doppler signals in good quality. Data with apparently poor signals were excluded. The NIRS data were obtained from a series of rSO_2 data by matching the time of measurement.

For statistical analysis, the values were expressed as the mean ± standard deviation. The correlation between data from the two modalities was examined by means of linear correlation analysis, and the difference of mean values was examined by means of the Mann-Whitney U-test using a statistical software, Stat View 5.0J (Abacus Concepts, CA, USA). Statistical significance was determined when the p value was less than 0.01.

Abbreviation list

CRAD-Vmax: Maximum flow velocity of the central retinal artery Doppler. TCD-Vmax: Maximum flow velocity of the transcranial Doppler. rSO_2: Regional tissue oxygen saturation. CPB: Cardiopulmonary bypass. BPmax: maximum blood pressure. RT: Rectal temperature. Hb: Hemoglobin concentration.

Table 1. A summary of the measurements in 184 data sets in 25 patients.

Preset stages	CRAD-Vmax (cm/s)	TCD-Vmax (cm/s)	rSO_2 (%)	BPmax (mmHg)	RT (degree)	Hb (g/dl)	Data numbers (*)
Before CPB	6.6 ± 2.2	41.0 ± 13.4	68.4 ± 6.6	113 ± 29	36.6 ± 0.4	11.1 ± 1.5	25 (0)
On CPB	4.8 ± 1.9	27.0 ± 10.1	66.8 ± 6.5	81 ± 22	35.7 ± 1.0	7.5 ± 2.2	26 (1)
During cooling	3.5 ± 1.5	21.6 ± 8.0	65.5 ± 6.0	62 ± 20	33.6 ± 1.2	6.3 ± 1.2	27 (7)
Under total CPB	3.3 ± 1.3	17.1 ± 7.7	65.2 ± 5.6	57 ± 17	33.1 ± 0.7	6.4 ± 0.9	26 (6)
During rewarming	3.7 ± 1.6	22.0 ± 8.7	65.6 ± 5.6	64 ± 20	34.1 ± 1.3	6.8 ± 1.2	28 (5)
During weaning	5.8 ± 2.0	33.0 ± 7.5	67.5 ± 6.2	94 ± 18	36.2 ± 0.8	7.3 ± 1.4	27 (1)
After CPB	6.9 ± 2.0	41.3 ± 11.5	68.6 ± 6.2	112 ± 21	36.6 ± 0.5	9.1 ± 1.1	25 (0)

One hundred and seventy five data were obtained from the 7 preset stages and an additional 9 data were measured during periods of varying blood pressure greater than 30 mmHg in a minute. Twenty missing data in the TCD measurement are expressed in parentheses (*). Values are expressed as mean ± standard deviation. (CRAD-Vmax: Maximum flow velocity of the central retinal artery Doppler. TCD-Vmax: Maximum flow velocity of the transcranial Doppler. rSO_2: Regional tissue oxygen saturation. CPB: Cardiopulmonary bypass. BPmax: Maximum blood pressure. RT: Rectal temperature. Hb: Hemoglobin concentration).

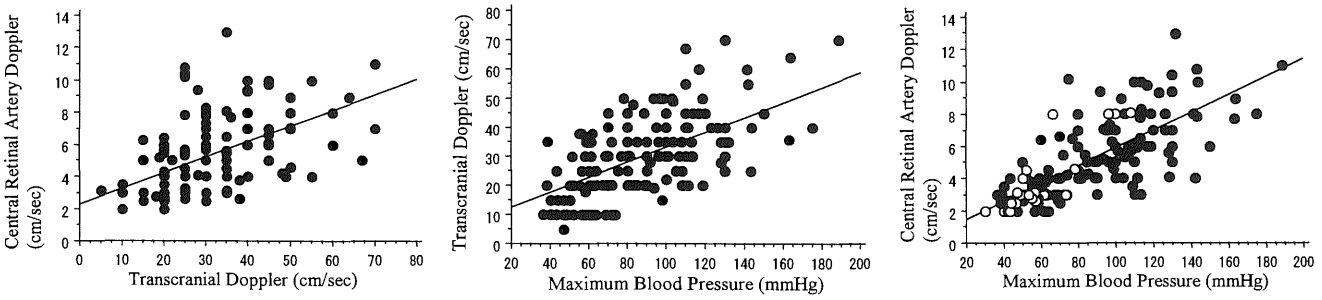

Fig. 1. Relationship between maximum blood pressure (mmHg) and Doppler studies. Maximum flow velocity (Vmax, cm/sec) of the transcranial Doppler (TCD) versus Vmax of the central retinal artery color Doppler (CRAD) (Fig. 1A). TCD-Vmax versus maximum blood pressure (Fig. 1B). CRAD-Vmax versus maximum blood pressure. The 20 open circles show the data corresponding to the missing data in TCD (Fig. 1C).

RESULTS

Clinical outcomes

There was no in-hospital mortality and morbidity in this series. No patient had any complication related to the monitoring which necessitated consultation to the neurologist or ophthalmologist.

Data acquisition

A total of 184 data sets were obtained (7 stages times 25 patients plus 9 additional data sets for patients who exhibited blood pressure changes of more than 30 mmHg) (Table 1). In case of TCD, data acquisition was failed in 20 of 184 data because of poor signal quality. This occurred in the stage during CPB. The BPmax of these missing data was low, ranging from 30 to 108 mmHg (59 ± 20 mmHg); lower than 60 mmHg in 14 of 20 data. There was no missing data in CRAD and NIRS.

TCD data versus CRAD data

Correlation between the TCD- and CRAD-Vmax was examined in 164 data where both data were obtained. The TCD-Vmax was significantly correlated to the CRAD-Vmax ($r=0.544$, $p<0.0001$: Fig. 1A).

To evaluate data variance in TCD and CRAD, the correlation between Doppler-derived Vmax and BPmax from the arterial monitor was analyzed by each of two methods. The correlation coefficient was 0.607 in TCD ($n=164$, $p<0.0001$, Fig. 1B) and 0.742 in CRAD ($n=184$, $p<0.0001$, Fig. 1C), slightly higher in the latter.

To eliminate the influence of variance among individual cases, the above statistical analysis was done in a single case in which the largest number of data were obtained ($n=13$). The TCD-Vmax was highly correlated to the CRAD-Vmax ($r=0.859$, $n=13$, $p<0.0001$, Fig. 2A). Correlation between the Doppler-derived Vmax and BPmax was lower in TCD than in CRAD ($r=0.930$ in TCD and $r=0.983$ in CRAD, $n=13$ for both, Fig. 2B, 2C).

Validity of CRAD-data corresponding to the missing data in TCD

To examine the validity of 20 CRAD-data corresponding to the missing TCD-data, these 20 data were plotted in a CRAD-Vmax to BPmax graph (Fig. 1C: open circles). They distributed similarly to the remaining 164 data. The CRAD-Vmax was significantly correlated to the BPmax in these 20

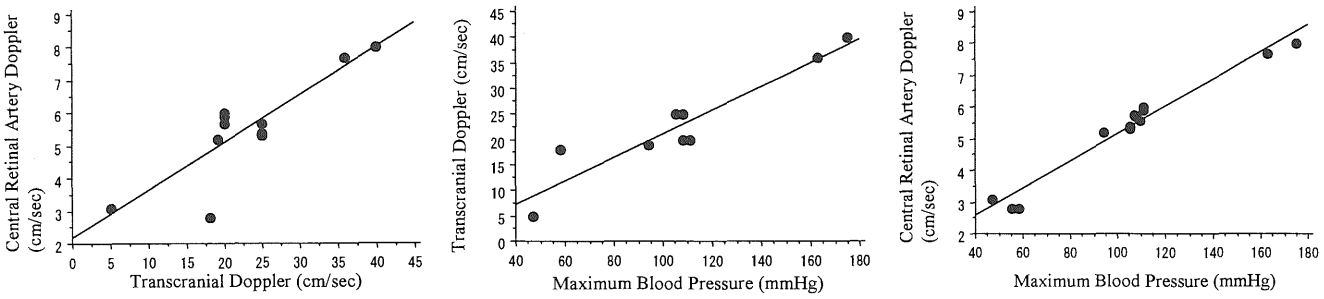

Fig. 2. Relationship between maximum blood pressure (mmHg) and Doppler studies in a single patient. Maximum flow velocity (Vmax, cm/sec) of the transcranial Doppler (TCD) versus Vmax of the central retinal artery color Doppler (CRAD) (Fig. 2A). TCD-Vmax versus maximum blood pressure (Fig. 2B). CRAD-Vmax versus maximum blood pressure (Fig. 2C).

Table 2. Comparison between the rSO_2 data sets above 60 % (Group1) and below 60 % (Group 2). Values are expressed as mean ± standard deviation.

	Group 1 (175 data sets)	Group 2 (9 data sets)	p-value
CRAD-Vmax (cm/s)	5.2 ± 2.4	3.0 ± 0.4	0.0012
TCD-Vmax (cm/s)	30.0 ± 13.0*	28.0 ± 16.4**	0.5500
BPmax (mmHg)	85.9 ± 31.1	66.2 ± 32.2	0.0601
RT (degree)	35.2 ± 1.6	34.0 ± 1.5	0.0300
Hb (g/dl)	7.9 ± 2.1	7.4 ± 1.8	0.7289

(CRAD-Vmax: Maximum flow velocity of the central retinal artery Doppler. TCD-Vmax: Maximum flow velocity of the transcranial Doppler. rSO2: Regional tissue oxygen saturation. BPmax: Maximum blood pressure. RT: Rectal temperature. Hb: Hemoglobin concentration).
*: n = 157 data sets (in the calculation of the TCD-data, 18 missing data were excluded.)
**: n = 7 data sets (in the calculation of the TCD-data, 2 missing data were excluded.)

data sets (r=0.727, p<0.0001).

NIRS data analysis

We recognized that rSO_2 changes were not instantaneous when blood pressure dropped and that the BPmax was not the only parameter for the rSO_2 drop. When the rSO_2 was simply compared with BPmax, the correlation coefficient was low (r=0.132, n=184, p=0.0735).

Since a drop of rSO_2 below a critical level is related to an occurrence of perioperative neurological events (unpublished data), we divided the 184 data into two groups according to their rSO_2 value: Group 1 ($rSO_2 \geq 60\%$, n=175) and Group 2 ($rSO_2 < 60\%$, n=9). All nine data in Group 2 were those during CPB. The CRAD-Vmax was significantly lower in Group 2. However, there was no significant difference in TCD-Vmax, BPmax, rectal temperature, or hemoglobin concentration between Group 1 and 2 (Table 2).

DISCUSSION

Validity of CRAD

The CRAD is a rather new monitoring modality and needs to be evaluated for accuracy of data and sensitivity. The gold standard available, if any, would be TCD. The CRAD-Vmax was well correlated to the TCD-data in this study, although the correlation coefficient was not very high (r=0.544). There are several possible reasons for this mild discrepancy in data between these two modalities: 1) variance among individual cases; 2) difference in the sampling site between CRAD and TCD; and 3) technical error in detecting the best signal. To avoid variance among individual cases, we examined the correlation between the CRAD- and TCD-Vmax in a single patient. The correlation coefficient was high. In the current study, we measured the blood flow velocity in the middle cerebral artery with TCD, not the ophthalmic artery, because the former is the most commonly used for sampling. As shown in Fig. 2A, the CRAD-Vmax was highly correlated to the TCD-Vmax in a single case except for one datum. It appears that the Vmax measurement is influenced less by the sampling site but more by technical factors.

Technical difficulty in obtaining a good signal is often encountered in TCD[12,13,21]. Although the use of duplex scan as a guide for sampling might reduce this problem, it is not clear whether the target artery can be clearly identified during CPB with low perfusion pressure and low blood flow velocity.

Our results suggest that CRAD can be a substitute for TCD when one needs to know whether the cerebral perfusion is severely impaired or not, in spite of a minor discrepancy of data between these two modalities.

Comparison between CRAD and TCD

It is too early to determine the superiority

between CRAD and TCD from the results of this study. However, our results suggest that CRAD is advantageous for monitoring cerebral perfusion during cardiac surgery because: 1) CRAD provides information about Vmax even when a reliable signal is not obtained in TCD, as in the 20 missing data of this study; 2) the correlation coefficient between BPmax and Doppler-derived Vmax was higher in CRAD than in TCD; 3) visualization and data sampling is easier in CRAD; and 4) the insonation angle can be nearly 0 degree with a guide of color flow imaging in CRAD, while it is not clear in the conventional TCD.

A possible complication of CRAD is orbital tissue damage by the ultrasound energy[1,10,14]. We used the lowest level of ultrasound output and avoided continuous exposure to ultrasound to prevent the occurrence of any CRAD-related complication. The clear visualization of arteries in CRAD facilitated the obtaining of data in the minimal period of time, leading to minimal exposure to ultrasound. As a result, we experienced no complication in this series. This is another reason why we did not use the ocular approach of TCD, where it takes time to find a good sampling position.

Relationship between CRAD- and NIRS-data

The NIRS is considered to provide information on the chromophore concentration change in the small region of the cortex where the probe is positioned, and has been introduced as a noninvasive real-time monitor for cerebral perfusion during cardiac surgery[7,9,18]. Several investigators reported that there is a correlation between rSO_2 and internal jugular venous oxygen saturation, and that a blood pressure alteration may not change the oxygen saturation because hypothemia reduces oxygen demand in the brain[4,5,11,16,17].

We ascertained that there is little change in rSO_2 immediately after the blood pressure changes and that the rSO_2 slowly drops when low perfusion pressure is sustained. The rSO_2 drop appears to be more apparent when the hemoglobin concentration is low or body temperature is not low enough (Table 1). This study demonstrated that the correlation between rSO_2 and BPmax was weak. A lowered rSO_2 below 60% was predominantly recorded when CRAD-Vmax was low. In contrast, interestingly, such a difference was not found in TCD-Vmax. These results suggest that low rSO_2 might indicate a critically lowered blood supply to the neural tissue, in spite of detectable blood flow in a larger artery such as the middle cerebral artery.

Limitation of this study

In this series, we did not use a duplex scan TCD but a conventional TCD[2] because the former system occupies a large space in the operating theatre. This might have caused an increased number of missing data. However, color Doppler TCD may solve technical problems during CPB. A further study needs to be planned in future to compare CRAD and color Doppler TCD.

The sampling sites were different among the three modalities: the central retinal artery in CRAD, the middle cerebral artery in TCD, and the brain tissue of the frontal lobe in NIRS. However, these three regions are perfused from the carotid artery. Thus, a decreased value of any monitor indicates an occurrence of hypoperfusion in the carotid system.

CONCLUSION

In conclusion, CRAD may be used as a substitute for TCD or even as a superior modality to TCD with less missing data, especially when the perfusion pressure is low. This is advantageous for monitoring cerebral perfusion in cardiovascular surgery using CPB. The CRAD data, unlike the TCD data, were related to an occurrence of unusually low rSO_2 and can be relevant to neural tissue perfusion.

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