Internal Jugular Bulb Blood Velocity as a Continuous Indicator of Cerebral Blood Flow during Open Heart Surgery

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Background: Most techniques for measuring cerebral blood flow (CBF) can not be performed rapidly enough to detect sudden changes in CBF. However, measurement of internal jugular bulb (IJB) blood velocity may offer real-time information on changes in CBF. In the current study, we measured IJB blood velocity and CBF in anesthetized humans.

Methods: In protocol 1, IJB blood velocity was continuously measured using an intravascular Doppler catheter during cardiac surgery under hypothermic cardiopulmonary bypass (CPB). CBF values obtained with a Kety-Schmidt method using inhalation of 30% argon in oxygen gas were compared with concurrent IJB blood velocity values in ten patients. A 3-French intravascular Doppler catheter was placed in the right IJB, and CBF measurements were made before CPB, in a stable hypothermic period during CPB, at rewarming during CPB, and after CPB. In protocol 2, dimensions of right IJB were observed before and during CPB using an intravascular rotating A scan ultrasonic catheter (5-French) in three patients.

Results: IJB blood velocity responded quickly to changes in arterial pressure or body temperature during CPB. The percent change in IJB blood velocity relative to pre-CPB value showed a good linear correlation with the percent change in CBF (%CBF = 0.87 × %IJB velocity + 17, r = 0.87). The mean difference between percent changes in CBF and IJB blood velocity was −5.6% and the standard deviation was 16%. Despite a large reduction in arterial pressure or IJB pressure, there were no significant changes in the IJB dimension.

Conclusions: The results suggest that IJB blood velocity may represent a clinically useful monitor of changes in CBF in anesthetized humans. (Key words: Brain: blood flow; blood velocity. Hypothermia: induced. Measurement techniques: transvenous endovascular ultrasonography.)

CEREBRAL blood flow (CBF) is influenced by several factors, including cerebral perfusion pressure, arterial

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carbon dioxide tension, body temperature and anesthetics. During surgery with hypothermic cardiopulmonary bypass (CPB), these factors may affect the cerebral circulation in an unpredictable manner. Recently, Nakajima et al. reported that continuous measurement of internal jugular bulb (IJB) oxyhemoglobin saturation was useful for the monitoring of cerebral oxygen balance during surgery with hypothermic CPB.[1] Because IJB oxyhemoglobin saturation is determined by both CBF and oxygen consumption of the brain, a reduction in jugular bulb oxyhemoglobin saturation could reflect either a decrease in CBF or an increase in cerebral oxygen demand. Thus, real-time information on CBF is required for a full understanding of cerebral conditions.

CBF can be intermittently assessed by the Kety-Schmidt method using an inert gas (argon or nitrous oxide)[2] or by the indicator dilution technique using a radiolabeled substance.[3] However, these techniques are slow in assessing CBF and require stable conditions. Thus, when there are rapid changes in the cerebral circulation, dynamic changes in CBF may not be accurately reflected by these methods. Transcranial Doppler method is one alternative for assessing cerebral circulation in a continuous and real-time mode when the size of a target cerebral artery is relatively constant.[4–7] However, it has not been confirmed that diameter of a target cerebral artery is constant without regard to large changes in arterial pressure during open heart surgery. Measurement of IJB blood velocity may give real-time CBF information provided the diameter of the jugular bulb remains constant. In fact, unlike that of the cervical jugular vein, the diameter of the IJB is indeed likely to be constant because it is enclosed by dura mater and cranial bone. In the current study, we examined the validity of the use of jugular bulb blood velocity as an estimate of CBF in anesthetized humans during open heart surgery.

Material and Methods

The study protocol was approved by the institutional ethical committee, and informed consent was obtained from each patient. Thirteen patients were enrolled. Two protocols were used. First, CBF was measured with a Kety-Schmidt method[2] using argon inhalation during open heart surgery involving hypothermic CPB and these data were compared with concurrent IJB blood velocity values. In the second protocol, the constancy of IJB size was observed using an intravascular rotating ultrasound catheter.

Protocol 1

Data were obtained from ten patients (58–77 yr old) scheduled for heart surgery or ascending aortic surgery under hypothermic CPB. None of the patients studied had any abnormal neurologic finding before surgery. One hour before anesthetic induction, the patients received 10 mg of morphine and 0.5 mg of scopolamine intramuscularly. After anesthetic induction by intravenous administration of fentanyl ($5-10 \ \mu g \cdot kg^{-1}$), diazepam ($0.1-0.2 \ mg \cdot kg^{-1}$) and vecuronium ($0.2 \ mg \cdot kg^{-1}$), the tracheas were intubated and the lungs were ventilated mechanically to maintain normocapnia. A radial artery was cannulated and a 7.5-French pulmonary arterial catheter was inserted from the right internal jugular vein through a 8-French introducer sheath. A nasopharyngeal probe was inserted for the monitoring of body temperature. Anesthesia was maintained with fentanyl ($50-70 \ \mu g \cdot kg^{-1}$) and diazepam ($0.2-0.6 \ mg \cdot kg^{-1}$) with inhalation of 50% nitrous oxide in oxygen.

During CPB, a nonpulsatile pump flow of 2.0–3.0 $l \cdot min^{-1} \cdot m^{-2}$ was maintained using a membranous oxygenator (Mera Excelung), arterial line filter and blood free priming solution. Hypothermia was induced (25–29°C) and maintained for at least 0.5 h. Arterial carbon dioxide tension was maintained at approximately 30 mmHg measured at 37°C and uncorrected for body temperature (α-stat). The patients were subsequently rewarmed to over 34.5°C and separated from the CPB.

CBF measurements with a Kety-Schmidt method[2] using argon inhalation[8] were made before CPB, in the stable hypothermic period during CPB, after rewarming and before separation from CPB, and after CPB during surgery. CBF values from the argon inhalation were compared with concurrent IJB blood velocity values. Measurements in each patient were done under the same postural conditions (no tilting) and with the same degree of sternal opening as possible.

Internal Jugular Bulb Doppler Velocimetry. After induction of anesthesia, the right internal jugular vein was cannulated with a 4-French introducer sheath (1.3 mm in diameter) at the level of the thyroid cartilage in the cephalad direction (at a more cephalad point of the pulmonary catheter insertion). A Doppler catheter was placed in the right IJB through the sheath with the assistance of fluoroscopy. We used a commercially available 3-French Doppler catheter with an ultrasound crystal mounted at the tip (1 mm in diameter, DC-201, Millar, Houston, TX) and a standard signal generator (MDV-20, Millar).[9-11] The carrier frequency was 20 MHz and the pulse repetition frequency 62.5 kHz. The sample volume was 0.46 mm in depth and was movable within the range of 1–10 mm from the catheter tip. The catheter tip position was adjusted so as to obtain a maximum velocity in the bulb; the blood velocity was sampled at a distance of 3–6 mm in front of the catheter tip. The depth of the introducer sheath was adjusted so that the tip of the Doppler catheter was out of the sheath by 5 mm or less. After sternotomy and placement of the sternal retractor, when the magnitude of the Doppler signal was decreased, the head was slightly rotated to readjust the catheter tip position to obtain a maximum signal. Then, the position of the head was not changed throughout the study. Analysis of Doppler signals was made using a zero crossing counter. Mean velocity was obtained using an analog filter (0.25 Hz) and recorded on a chart recorder (Omnicorder 8M14, Nihondenki-Sanei, Japan) and/or on a computer through an AD converter every 5 s.

Cerebral Blood Flow Measurement with the Argon Inhalation Method. CBF was measured using a Kety-Schmidt method[2,8] involving a 15 min period of inhalation of 30% argon in oxygen gas. During argon inhalation, arterial and IJB blood were sampled intermittently through the radial arterial catheter and the tip of the internal jugular sheath, respectively. Blood argon concentration was measured with a mass spectrometer (Medispect II, Chemetron, MO). Calculation of CBF was done by an investigator who was not involved with the IJB blood velocimetry.

Protocol 2

In this protocol, the constancy of IJB size was examined. In each of three additional patients who had open heart surgery under CPB, we measured the dimensions of right IJB before and during CPB using an intravascular rotating A-scan ultrasound catheter system (Ultrasound Imaging System, C-VIS, Sunnyvale,
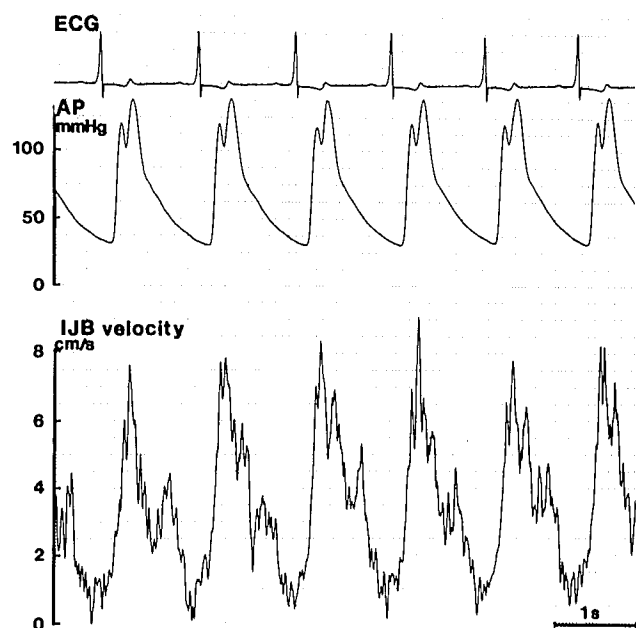
Fig. 1. Instantaneous internal jugular bulb (IJB) blood velocity and arterial pressure (AP) recordings. The velocity increases synchronously with arterial pulsation.

CA).[12,13] Anesthesia was performed as in protocol 1. The intravascular ultrasound catheter (C1000, C-VIS, 5-French, 30 MHz) was placed in the right IJB through an introducer sheath (5-French) under general anesthesia and the position of the catheter tip was adjusted with the aid of fluoroscopy and an echographic view of the IJB. During surgery, the dimensions of the IJB, IJB pressure, and arterial pressure were recorded.

Data Analysis

Data were expressed as mean ± SD. In the comparison of IJB blood velocity with CBF, a linear correlation analysis was done. To show the relation between relative changes in the two parameters, percentage changes relative to pre-CPB values were calculated, and a linear correlation analysis between the two parameters was done for each protocol. With regard to relative changes in the two parameters, the bias and precision for the data sets were determined by calculating the mean difference and the standard deviation between the parameters as described by Bland and Altman.[14] Changes in CBF and IJB blood velocity and other variables during surgery were analyzed using analysis of variance and a post hoc Dunnett's test.

Results

Protocol 1

Figure 1 shows an instantaneous wave form of the IJB blood velocity at pre-CPB period. The velocity increases synchronously with the arterial systolic phase (atrial diastolic phase). The velocity pattern was not pulsatile during CPB. Figure 2 shows a representative trend of body temperature, mean IJB blood velocity and mean arterial pressure averaged every minute during cardiac
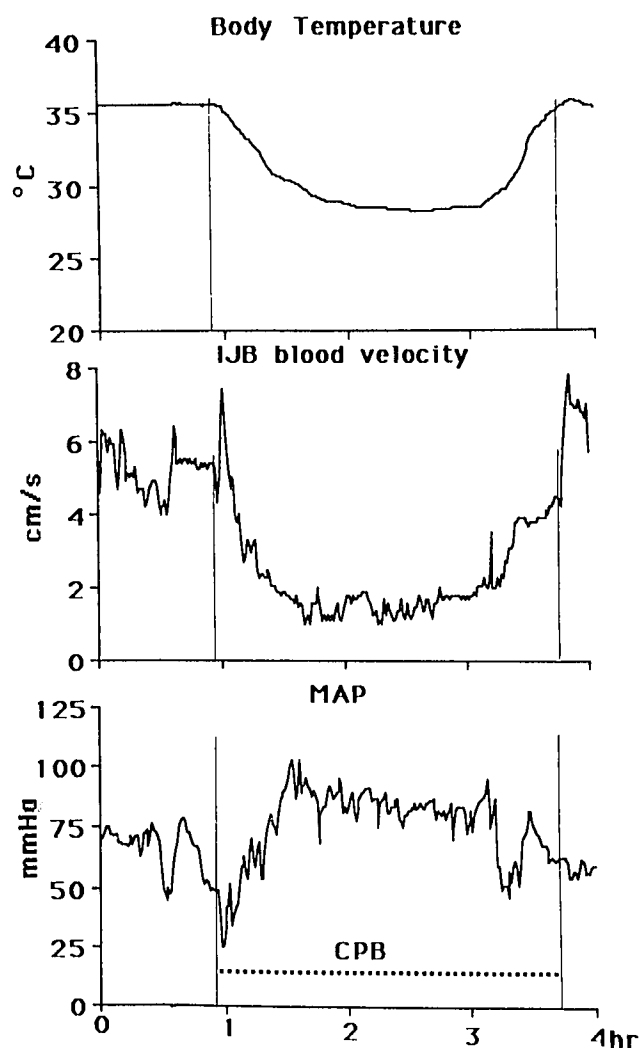

Fig. 2. Trends of body temperature, mean internal jugular bulb (IJB) blood velocity, and mean arterial pressure (MAP) during cardiac surgery. Immediately after initiation of cardiopulmonary bypass, IJB blood velocity decreased transiently, followed by a short period of overshoot. The velocity then decreased with the decrease in body temperature.

surgery. Immediately after the start of CPB, IJB blood velocity decreased with the initial decrease in arterial pressure followed by a transient increase in the velocity over the baseline level for several minutes. Then, IJB blood velocity decreased as cooling progressed and reached its lowest level during the stable hypothermic stage. During the rewarming period, IJB blood velocity was restored as body temperature increased. Such changes in IJB blood velocity were observed in all patients. The duration of CPB was 168 ± 69 min. Table 1 shows the values during cardiac surgery of variables that affect the cerebral circulation. CBF and IJB blood velocity at pre-CPB were 36 ± 9 ml·100 g^{-1}·min^{-1} and 6.0 ± 2.5 cm·s^{-1}. Both CBF and IJB blood velocity were significantly decreased during the hypothermic stage to 55 ± 17% and 48 ± 14%, respectively, of their pre-CPB control value. However, in the rewarmed stage they were restored to levels not significantly different from their control values.

Figure 3 shows a comparison between CBF measured with the Kety-Schmidt method[2] and IJB blood velocity in lumped data from ten patients. Although the parameters show a positive correlation, the points are widely scattered, and the correlation between the parameters' absolute values is not good. To enable comparison between relative changes, the parameters were plotted as a percentage of the pre-CPB control value in each patient. Figure 4 shows the relation between the changes in the two variables in the lumped data from ten patients. IJB blood velocity as a percentage of the
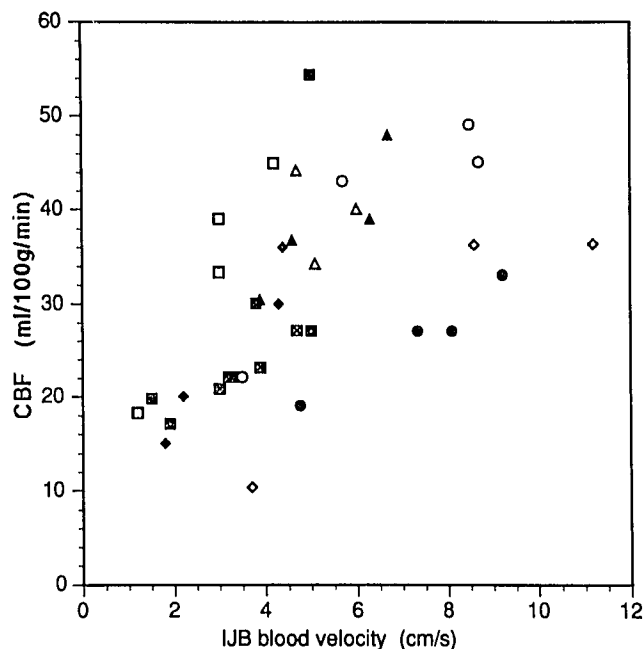

Fig. 3. Comparison between internal jugular bulb (IJB) blood velocity and cerebral blood flow (CBF) during cardiac surgery with hypothermic cardiopulmonary bypass. Each symbol indicates data from an individual patient.

pre-CPB value has a good linear correlation with the CBF (%CBF = 0.87 × %IJB velocity + 17, r = 0.87). The mean difference between CBF and IJB blood velocity as a percentage of the pre-CPB value was −5.6%

Table 1. Changes in Variables during Cardiac Surgery

	Pre-CPB	Hypothermia	Rewarmed	Post-CPB
N	10	9*	8*	9*
MAP (mmHg)	79 ± 14	71 ± 9	68 ± 14	75 ± 9
Hb (g/dl)	10.4 ± 0.6	6.6 ± 0.9†	7.6 ± 1.2†	9.7 ± 1.6
Temp (°C)	35.8 ± 0.7	28.3 ± 1.6†	36.3 ± 0.8	35.5 ± 0.7
Pa_{CO_2} (mmHg)	35.7 ± 2.3	29.7 ± 5.2†	30.4 ± 6.7†	35.7 ± 2.2
Pa_{O_2} (mmHg)	341 ± 98	563 ± 75†	310 ± 56	222 ± 121
Velocity (cm/s)	6.0 ± 2.5	2.8 ± 1.2†	5.0 ± 2.5	5.7 ± 1.4
CBF (ml·100 g^{-1}·min^{-1})	36 ± 9	19 ± 5†	33 ± 10	36 ± 7
CMR_{O_2} (ml·100 g^{-1}·min^{-1})	2.3 ± 0.7	0.9 ± 0.3†	1.9 ± 0.8	2.1 ± 0.7
Sv_{JO_2} (%)	58.7 ± 10.2	65.7 ± 6.5†	54.0 ± 8.9	58.9 ± 7.3

Data are mean ± SD.

CPB = cardiopulmonary bypass; Pre-CPB-before CPB (control); Hypothermia = a stable hypothermic period during CPB; Rewarmed = a rewarmed period before weaning from CPB; Post-CPB = after CPB during surgery; MAP = mean arterial pressure; Hb = hemoglobin concentration; Temp = nasopharyngeal temperature; Velocity = internal jugular bulb blood velocity; CBF = cerebral blood flow; Sv_{JO_2} = oxyhemoglobin saturation of internal jugular bulb blood; CMR_{O_2} = cerebral metabolic rate for oxygen.

* One or two measures were missed due to technical failure in CBF measurement.
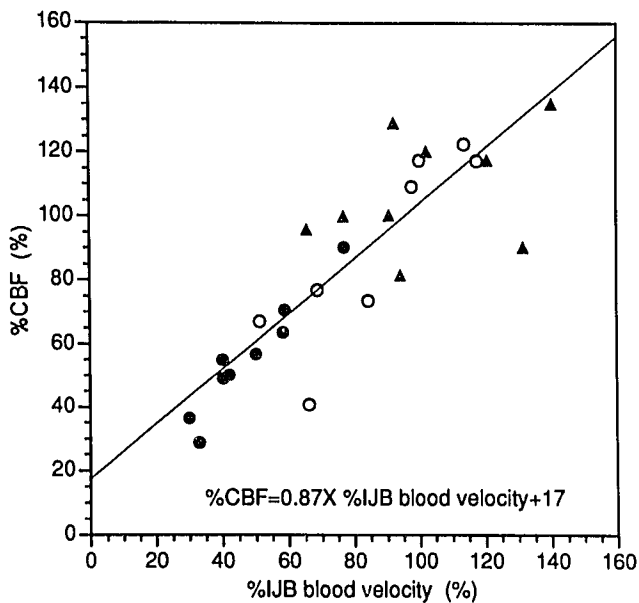
† P < 0.05 *versus* pre-CPB value.

Fig. 4. Comparison of changes in internal jugular bulb (IJB) blood velocity and cerebral blood flow (CBF) relative to pre-CPB control. Filled circles = hypothermic period; open circles = rewarming period; triangles = after cardiopulmonary bypass.

and the standard deviation was 16%. Correlation of the two percent-change parameters at each period was 0.92 at the hypothermic period, 0.88 at the rewarmed period and 0.39 at the post-CPB period.

Protocol 2

Only a slight motion of the venous wall in time with the heart beat was observed using intravascular echography. Figure 5 shows echographic views of an IJB before CPB, just after the initiation of CPB, and as the hypothermic period advanced. Despite large reductions in IJB pressure (from 6 to 2 mmHg) and mean arterial pressure (from 76 to 37 mmHg), the size of the IJB did not change significantly (8.9–9.1 mm). In the other two patients, without regard to a similar degree of reduction in arterial pressure and IJB pressure, or cooling, the dimensions of the IJB were not changed significantly (7.8–7.9 mm in the second patient and 6.9–6.7 mm in the third patient).

Discussion

The current study demonstrates a good linear correlation between IJB blood velocity and CBF as a per-

centage of the pre-CPB value. IJB blood velocity rapidly responded to changes in CBF induced by alterations in body temperature or arterial pressure. However, the absolute values of IJB blood velocity did not enable comparison between individuals in terms of their CBF level. This is because both the dimensions of the IJB and the insonation angle between the blood stream and the Doppler beam differ among subjects. In any case, when there are dynamic changes in cerebral circulation, as in hypothermic CPB, rapid access to the relative changes in CBF is valuable as well as estimation of absolute CBF.

In the current study, the right internal jugular venous blood flow was assumed to represent a constant part of the venous drainage from the brain. The major part of the CBF passes through both internal jugular veins, although a small portion is drained by other veins, about 5% by the external jugular vein and less via the vertebral vein.[15] The distribution of internal jugular blood flow between the two sides is not always symmetric and the often large right jugular vein might drain more blood than the left.[16] The good correlation between the relative changes in CBF and IJB blood velocity suggested that no significant changes in bulb diameter or blood drainage distribution occurred during surgery. In protocol 2, it was confirmed that the dimensions of the IJB did not change significantly despite significant reductions in arterial pressure and IJB pressure. We did not record IJB dimensions in all the patients included in this study. However, we think that our finding that dimensions of the jugular bulb are constant can be extended to all the patients because of anatomic evidence that in its bulb part, the vein is surrounded closely by dura mater and cranial bone.[17] As far as the blood drainage distribution is concerned, it is unlikely that significant changes occur during surgery unless one internal jugular vein is compressed or postural changes are induced. In comparing IJB blood velocity and CBF as a percentage of the pre-CPB values using the Bland-Altman analysis,[14] the mean difference and the standard deviation between the two methods were −5.6% and 16%, and 95% of differences would be expected to lie between −37% and +26%. Because there is no "gold standard" method for CBF measurement, the variation of the differences can not be attributed to only measurement error of the IJB blood velocity.

The blood velocity pattern of IJB was pulsatile before CPB and became nonpulsatile during CPB. We assume that the pulsatile IJB blood velocity is generated by the pressure of the right atrium. A similar observation was
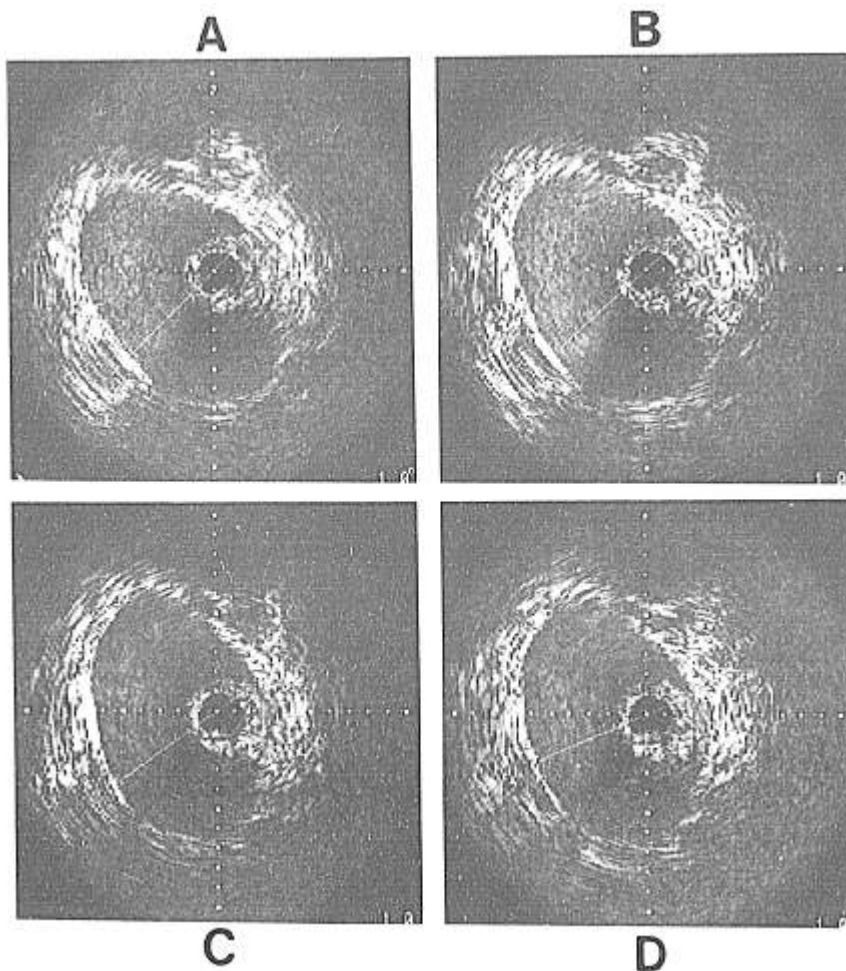
Fig. 5. Echographic views of internal jugular bulb (IJB) using an intravascular rotating ultrasound catheter (*A*) before cardiopulmonary bypass (CPB) (34.6°C, mean arterial pressure [MAP] 76 mmHg, internal jugular bulb pressure [IJBP] 6 mmHg); (*B*) just after the initiation of CPB (34.6°C, MAP 37 mmHg, IJBP 2 mmHg); (*C*) at 32.3°C body temperature during CPB (MAP 55 mmHg, IJBP 3 mmHg); and (*D*) at 30°C (MAP 75 mmHg, IJBP 2 mmHg). The outer oval structure shows the wall of IJB, and the central small round shadow shows the ultrasound catheter. One interval of central dotted line = 1 mm. The dimension of the IJB did not change significantly.

made by Sivaciyan and Ranganathan[18] and by Ranganathan *et al.*[19] They studied the relation of internal jugular vein blood velocity patterns and cardiac cycle or cardiac function using a transcutaneous ultrasonic Doppler flowmeter and observed two peaks of internal jugular blood velocity, one at the systolic phase that was initiated by atrial relaxation and one at the diastolic phase that occurred at right ventricular filling. In subjects with good cardiac function, the systolic flow is dominant, however, diastolic flow becomes dominant in a case of right heart failure.

During hypothermic nonpulsatile CPB, factors including body temperature, arterial blood gases, perfusion pressure, pump flow, and hemodilution affect both CBF and cerebral metabolic rate. Nakajima *et al.* measured the oxyhemoglobin saturation of the IJB continuously during cardiac surgery with hypothermic CPB

using an oximetric catheter and found that significant changes in saturation occurred after the initiation of CPB and during the rewarming period of CPB.[1] However, oxyhemoglobin saturation is a product of oxygen consumption (metabolic rate) and supply (CBF), and their data indicated that CBF did not change proportionally to changes in the cerebral metabolic rate of oxygen consumption at the periods. In the current study, changes in IJB blood velocity were well correlated with changes in CBF assessed using the Kety-Schmidt method.[2] The values of CBF and cerebral metabolic rate of oxygen consumption were slightly higher than those reported during open heart surgery using the xenon 133 clearance technique.[20] However, CBF and the cerebral metabolic rate of oxygen consumption showed changes during open heart surgery similar to those previously reported.[21-23] A transient biphasic al-

teration in IJB blood velocity was seen after the initiation of CPB in the representative trend. We believe that the initial decrease in velocity was due to a reduction in perfusion pressure to less than the CBF autoregulation range and the subsequent increment over the pre-CPB value was the result of hemodilution.[5] Our observations suggest that the IJB blood velocity method can follow such rapid changes in cerebral circulation.

Several methods are available for the estimation of CBF in the clinical situations.[21] Each method has both merits and limitations. Inert gas inhalation methods are commonly used,[2] but they are cumbersome and slow to assess CBF values. Furthermore, they require steady state conditions and allow only a limited number of measurements. The radioactive xenon technique[3] is available, but the potential hazard of pollution with nuclear substances would limit its use in an operation room. Transcranial Doppler measurement of middle cerebral artery velocity is noninvasive and can follow relative changes in CBF in a repetitive or continuous manner.[4-6] The dimensions of the middle cerebral artery are assumed to remain relatively constant because regulation of cerebrovascular resistance acts at the arteriolar level. A good correlation between relative changes in CBF and in middle cerebral artery blood velocity with transcranial Doppler has been demonstrated.[7] Transcranial Doppler has been used during cardiovascular surgery to detect microemboli,[24] to study CBF autoregulation and carbon dioxide reactivity.[25,26] However, it has not be unknown that the diameter of the middle cerebral artery is constant without regard to large reduction in arterial pressure such as in the initiation of CPB.

The IJB is located deeply at the skull base and enclosed within a bony structure. It is difficult for an ultrasound beam to reach the IJB from a skin surface noninvasively. We used two kinds of intravascular ultrasonic catheter in the current study. IJB blood velocity was measured with a Doppler catheter, which uses the changes in frequency of an ultrasonic beam as it reflects off a moving object (Doppler shift). For an echographic view of IJB, an A-scan ultrasonic rotating catheter was used, which provides a 360° cross-sectional image of a vessel in a perpendicular to the catheter tip. The Doppler catheter and its introducer sheath used were small, however, they might obstruct the internal jugular flow in some degree and distort the result of the current study. However, the cross-sectional area of the catheters are as small as 4% of that of the IJB in our data. Further, no significant pressure gradient was observed between IJB pressure and right atrial pressure in three of the patients in whom the two pressures were measured simultaneously. We do not think that these catheters significantly obstruct the right internal jugular blood flow. Acute increase or decrease in right atrial pressure can transiently affect the IJB blood velocity. However, when right atrial pressure level is kept high such as in tricuspid regurgitation, IJB blood velocity is supposed to represent CBF because an amount of blood into the brain is equal to the amount of venous blood outflow in a stable condition of cerebral venous capacitance system.

Our method quickly reflects alterations in CBF. However, stable recording of IJB velocity was often disturbed during cardiac surgery. In the IJB, blood flow is not completely laminar. With the current technique, the sampled volume of the blood stream with the Doppler catheter is so small that even a slight displacement of the catheter tip may cause great changes in the velocity measurement obtained. However, this shortcoming could be overcome by using a transducer with a wider divergence angle of the ultrasound beam, that is, by sampling a larger volume of the stream. Doppler reflection, which enables estimation of flow velocity, depends on the angle of insonation between the flow and the Doppler ultrasound. Procedures such as inserting or removing a sternal retractor, or postural changes like tilting (left, right, or head up or down) can lead either to an alteration in the insonation angle between the Doppler catheter tip and IJB blood stream or to displacement of the catheter tip. The worse correlation between the percent change in CBF and the percent change in IJB blood velocity after CPB could be explained by a slight displacement of the catheter tip resulting from the resetting of a sternal retractor for surgery. Rotation of the head likewise would change the insonation angle so that care needs to be taken not to change the position of the head during IJB blood velocity measurement. Moreover, changes in posture such as right or left tilting might possibly affect the distribution of the venous drainage.

In conclusion, we suggest that IJB blood velocity measurements give a continuous indication of changes in CBF during surgery when there are large hemodynamic changes, but that the absolute value of the velocity is not a reliable indicator of CBF. IJB blood velocimetry may be a useful tool for the assessment of the cerebral circulation during open heart surgery with hypothermic CPB.

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