Acta Neurochir (Wien) (1990) 105: 89–97

Acta Neurochirurgica

Haemodynamic Aspects of Clinical Cerebral Angiography
Concurrent Two Vessel Monitoring Using Transcranial Doppler Ultrasound*

H. Nornes, W. Sorteberg, P. Nakstad, S. J. Bakke, R. Aaslid, and **K.-F. Lindegaard**

Departments of Neurosurgery and Radiology (Neuroradiology Section), Rikshospitalet, The National Hospital, University of Oslo, Oslo, Norway

Summary

To overcome the technical limitations which have precluded noninvasive Doppler ultrasound in investigation of rapid cerebral haemodynamic responses in two cerebrovascular beds at the same time, we have modified a commercial 2 MHz pulsed Doppler instrument with online spectrum analysis. Two probes are activated intermittently, recording eight averaged Doppler-shifted spectra from each probe sequentially.

Concurrent recordings of blood velocity in both middle cerebral arteries were performed during 25 selective iohexol carotid angiography runs in 13 patients with near normal cerebral vasculature. The technique permitted the differentiation between the specific responses confined to the recipient vascular bed, and the general responses occurring in remote brain areas as well. The specific response to iohexol was biphasic; a significant decrease in blood velocity occurred < 4 s after the bolus entry, probably due to the high viscocity of iohexol. Between 4 and 12 s, blood velocity was significantly increased, reflecting the cerebrovascular response to hypertonic solutions. The blood velocity on the opposite side increased from < 4 s through 45 s after iohexol. This concurs with studies using electromagnetic flowmetry, and suggests that these general responses are elicited by anxiety, discomfort and pain. Thus, no general responses were seen during angiography under general anaesthesia.

Eight patients investigated during catheter flushing with normal saline showed a biphasic specific response reciprocal to that due to iohexol. A significant blood velocity peak occurred < 4 s after the bolus entry, followed by a decrease between 4 and 60 s. The saline injections produced no pain and evoked no significant general response.

Keywords: Blood flow velocity; cerebral angiography; cerebral arteries; iohexol; normal saline.

Introduction

Clinical investigations using electromagnetic flowmeters have shown the importance of investigating the blood flow in two cerebral arteries at the same time[18, 19]. One such study demonstrated a transient increase in the blood flow to both hemispheres during selective carotid angiography[19]. However, the necessity for flow probe implantation limits such studies to highly selected patients.

Transcranial Doppler (TCD) allows noninvasive measurements of the blood velocities in human basal cerebral arteries. The insight obtained into individual haemodynamic states may be further enhanced through recording from two arterial channels[8, 10] and from two different levels of one inflow channel[7, 9, 10, 12]. With conventional techniques the vessels of interest are investigated in series, which implies the assumption of stable haemodynamic conditions. Such investigation during acute circulatory changes therefore requires parallel recordings from two vessels. Technical limitations have previously precluded this.

We have modified a commercial TCD instrument with online spectrum analysis to enable concurrent measurements from two vessels. Two ultrasound probes are addressed sequentially, and eight spectrum analyses (about 0.1 s) are obtained from two different arteries intermittently. In the present study we have used this technique to investigate cerebral haemodynamics during clinical carotid angiography. Concurrent recordings of the blood velocity in both middle cerebral arteries (MCAs) during injections of iohexol and heparinized normal saline allowed a differentiation between the *specific responses* which are confined to the recipient vascular system, and the *general responses* which occur in remote brain areas as well. Blood velocity measurements from the distal extracranial internal carotid artery (ICA) and the MCA of the recipient hemisphere permitted comparisons of concurrent var-

* *Acknowledgement:* Supported by The Norwegian Council on Cardiovascular Diseases.

iations in blood velocity at two levels along one inflow channel.

Material and Methods

Sixteen patients, aged from 8 to 46 years (median 27 years) were investigated during selective carotid angiography under local anaesthesia. The indications for angiography, focal epilepsy considered for surgical treatment (14 patients), and tumour of the upper neck region (2 patients), seemed to permit the assumption of a near normal cerebral vasculature.

We also investigated a child, aged seven years, with an extracranial tumour, who underwent bilateral carotid angiography under general anaesthesia. The findings from this patient are considered separately.

Angiography and Saline Injections

Angiography was performed by the femoral route using Fr 5 catheters. Trial injections were limited to a minimum and performed never less than three minutes prior to the diagnostic injection. In the epileptic patients, the catheter tip was in the ICA about three cm above the common carotid bifurcation, and eight ml iohexol (300 mg I/ml) were injected as quickly as possible by hand. In the patients with neck tumour 10 ml iohexol were injected in the common carotid artery, the iohexol doses to the brain probably being equivalent in all patients. Catheter flushing with heparinized normal saline was performed as described for iohexol.

Blood Velocity

We used a 2 MHz range-gated pulsed wave Doppler instrument with online 64 point spectrum analysis (Trans-scan, made by EME, Überlingen, FRG). The blood velocity in the proximal MCAs (V_{MCA}) was recorded using self-retaining probes (FP-2, made by EME, Überlingen, FRG) strapped to the patient's head in the position providing the best signals[13]. Handheld probes were used for recording ICA blood velocity V_{ICA}).

Concurrent recordings were achieved by computer software modifying the realtime for the instrument. Two probes were activated intermittently, recording eight averaged Doppler spectra on each side sequentially. Figure 1 shows recording from both MCAs during left carotid angiography. The sampling time between each switching was about 0.1 s (Fig. 1 A–C). The information recorded during one monitor sweep (about 3.2 s) was transferred to hard disk and the next sweep was initiated. No data were acquired during the 0.6 s hard-disk write period.

Injection of iohexol and saline produced abnormally high amplitude signals from the recipient vessel. These signals were clearly different from the blood velocity signal, and were probably due to bolus gas bubbles[20]. The onset of these signals was taken as heralding the bolus entry and denoted T_0 (Fig. 1 B). A record spanning from time T to time T + 3.2 seconds was coded as being T + 1.6 s after T_0. The mean values of the outlines of the velocity spectra for each record were computed. The abnormal signals precluded analysis of the 1–3 s when the bolus passed the sampling area. When these ended less than half way through a record, the mean for the remainder of that record was calculated; otherwise such records were rejected.

Data Analysis

The average blood velocity from the 24–40 s (6–10 records) immediately preceding the injection was used as the baseline value for that run, with values obtained following the injections expressed as percentages of the baseline. The data are presented as the means and the 95% confidence intervals of the means, and ranges for the periods < 4 s, 4–8 s, 8–12 s, 12–20 s, 20–30 s, 30–45 s, 45–60 s, and 60–90 s after T_0. Analysis of differences was performed using the Wilcoxon rank-sum test for independent samples.

Results

Concurrent bilateral V_{MCA} measurements were performed during 25 injections (13 patients) with iohexol and 16 injections (8 patients) with heparinized normal saline. Concurrent recordings of the V_{ICA} and the V_{MCA} of the recipient hemisphere were carried out during three injections with iohexol and three injections with saline (3 patients). Thus, in the 16 patients having angiography under local anaesthesia, blood velocity measurements were performed during a total of 47 runs. Additionally, in a seven year old child investigated under general anaesthesia, bilateral V_{MCA} measurements were carried out twice during the injection of iohexol. These findings are treated separately.

There was no angiographic sign of precerebral or intracerebral artery stenosis, aneurysms, or arteriovenous malformations, and there were no dislocations of the major intracerebral arteries. The angiograms showed no evidence of contrast flow into the opposite MCA.

Concurrent Recordings of MCA Blood Velocity bilaterally

Iohexol: A transient decrease in the recipient MCA blood velocity ($V_{iohexol}$) was seen in the < 4 s period (Fig. 1). However, to assess this decrease quantitatively with the present technique, the bolus related abnormally high amplitude signals had to end early within a monitor sweep (Fig. 1 B). Therefore, the < 4 s period could only be assessed for 9 of the 25 runs (Fig. 2). From 4 through 30 s after T_0 $V_{iohexol}$ increased significantly. The highest mean value, 123%, occurred between 4 and 8 s (Fig. 2). In 20 runs the zenith occurred between 4 and 12 s, and between 12 and 30 s in the remaining five. The blood velocity in the opposite MCA ($V_{contralateral}$) was significantly increased from < 4 to 45 s after T_0, reaching a mean value of 107% between 8 and 12 seconds.

Normal saline: The blood velocity in the recipient MCA (V_{NaCl}) increased significantly during the < 4 s period (mean value 111%). Then V_{NaCl} decreased significantly from 4 through 60 s after T_0 (Fig. 3); however, the mean value was never below 92%. The $V_{contralateral}$ showed

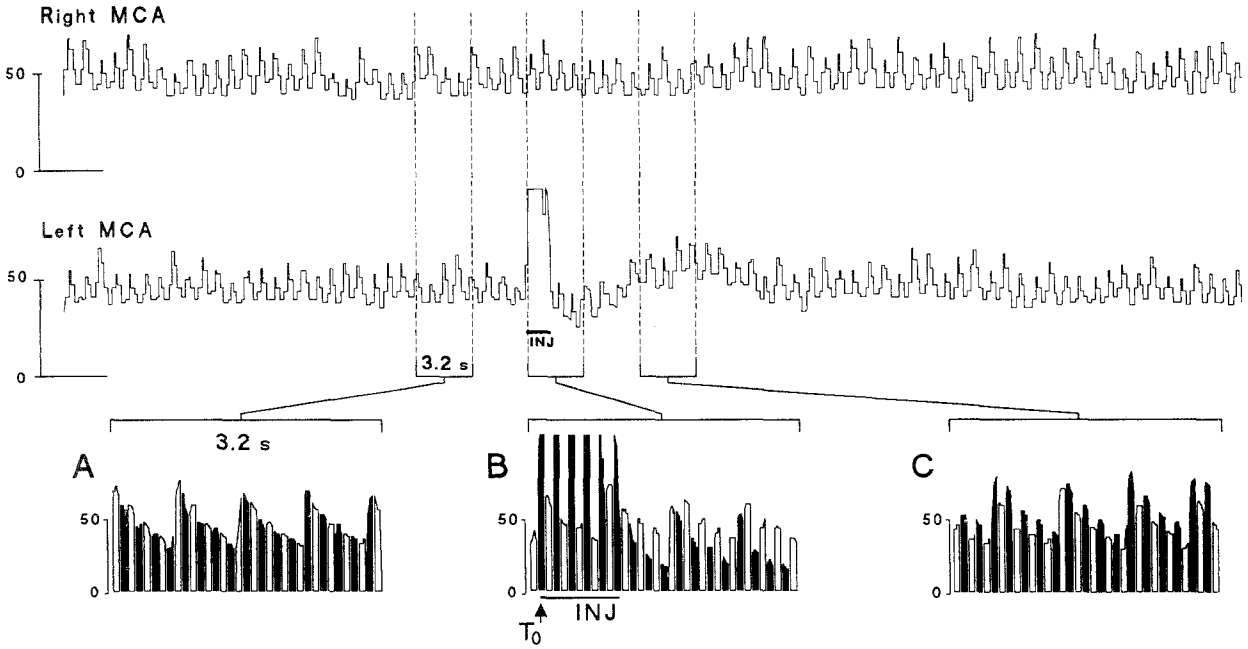

Fig. 1. Female, aged 38 years, focal epilepsy. Computer tracings of blood velocities recorded concurrently from the right (upper) and left (lower) middle cerebral arteries (MCAs) during left carotid iohexol angiography. The left MCA blood velocity shows a biphasic response, a marked decrease followed by a transient increase following the bolus entry (INJ). A–C Graphic representation of Doppler-shifted spectra recorded before (A), during (B), and after (C) the bolus injection. Recordings were obtained intermittently from the right (white columns) and the left (black columns(MCA concurrently. Each column represents eight averaged Doppler-shift spectra (about 0.1 s). The bolus passage (INJ) briefly produced abnormally high amplitudes in the recording from the left MCA (B). The onset of these signals was taken as heralding the bolus entry into the MCA and denoted T_0. The biphasic response to iohexol is clearly seen (B and C). Blood velocities in cm s^{-1}

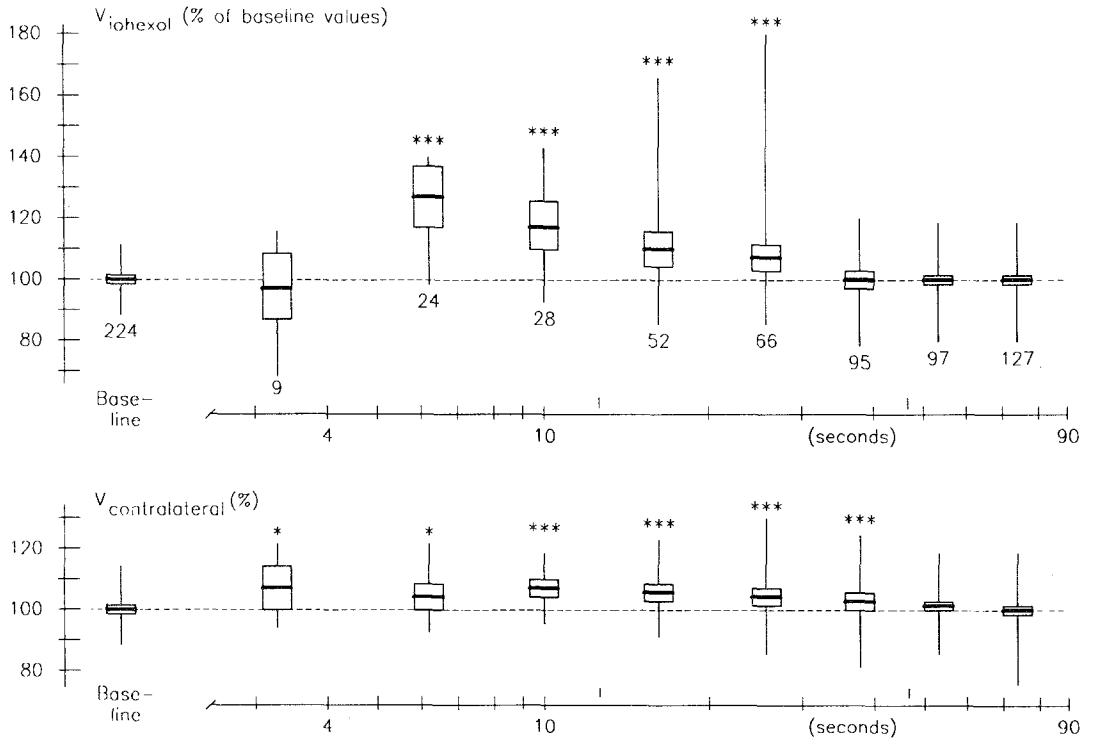

Fig. 2. Blood velocity in the recipient MCA ($V_{iohexol}$) and in the opposite MCA ($V_{contralateral}$) during 25 selective carotid iohexol angiography runs in 13 patients expressed as percentages against corresponding baseline values of 100%. The compiled data are shown as means, 95% confidence interval of the means, and ranges for the periods: < 4 s, 4–8 s, 8–12 s, 12–20 s, 20–30 s, 30–45 s, 45–60 s and 60–90 s after T_0 (see Fig. 1). $V_{iohexol}$ increased significantly from 4 to 30 s. $V_{contralateral}$ increased from < 4 to 45 s after T_0. Note logarithmic time scale. Numbers indicate number of runs evaluated. * $p < 0.05$; *** $p < 0.001$; Wilcoxon's rank test

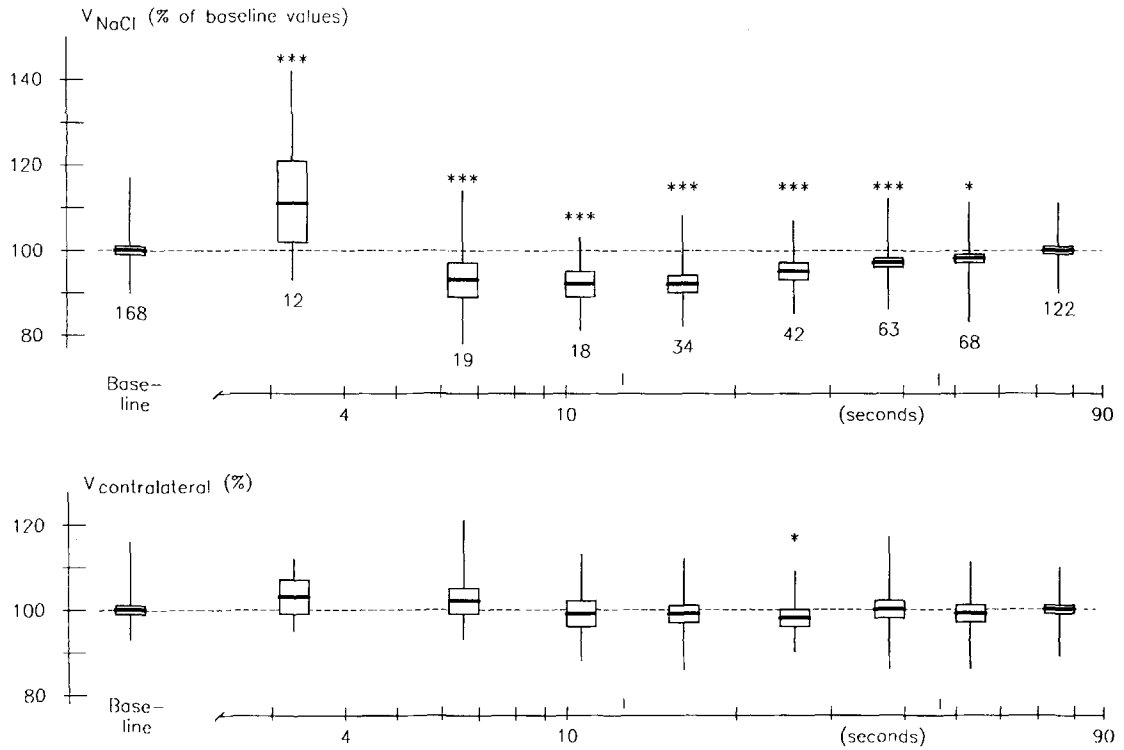

Fig. 3. Blood velocity in the recipient MCA (V_{NaCl}) and in the opposite MCA ($V_{contralateral}$) during flushing with heparinized normal saline. V_{NaCl} increased significantly during the < 4 s period, then remained significantly decreased between 4 and 60 s. $V_{contralateral}$ did not change apart from a slight decrease between 20 and 30 s. See Fig. 2 for symbols.

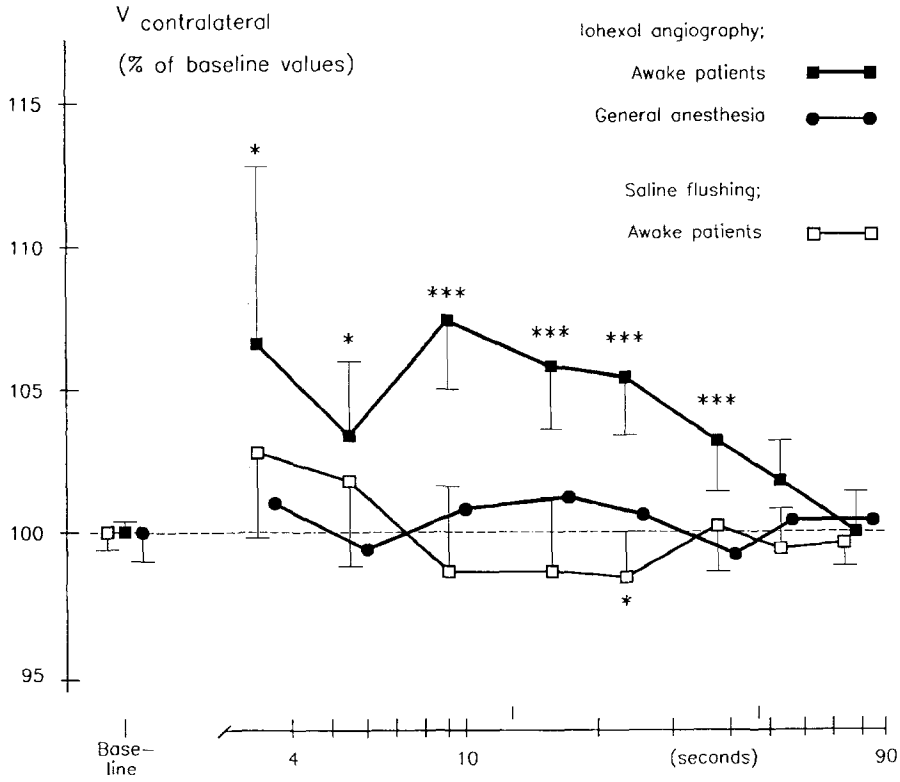

Fig. 4. Blood velocities in contralateral middle cerebral arteries ($v_{contralateral}$) during iohexol angiography and flushing with normal saline. $V_{contralateral}$ increased from < 4 to 45 s after iohexol (black squares), probably due to bolus related discomfort and pain. After normal saline (white squares) $V_{contralateral}$ did not change apart from a slight decrease between 20 and 30 s. No change in $V_{contralateral}$ was observed in a child who had angiography in general anaesthesia (black circles)

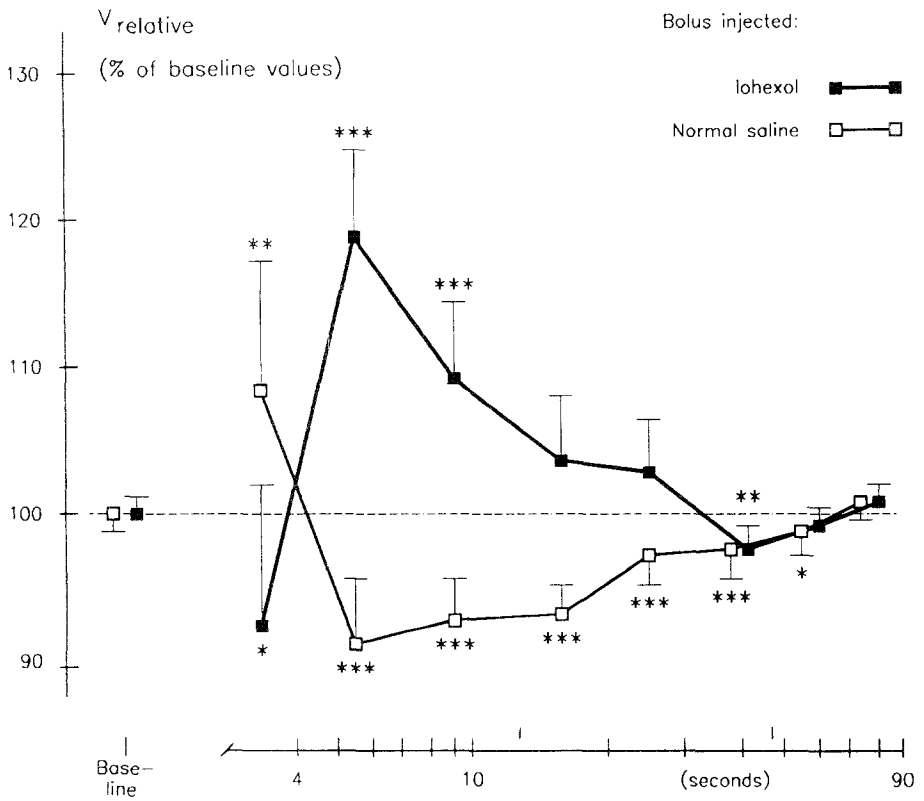

Fig. 5. The MCA blood velocity in the hemisphere tested ($V_{iohexol}$ and V_{NaCl}) was divided by the MCA blood velocity on the opposite side ($V_{contralateral}$), and expressed as an index ($V_{relative}$). The specific responses (see text), to iohexol (black squares) and to normal saline (white squares) were biphasic and mutually inverse

no significant change except between 20 and 30 s (mean value 98%).

Figure 4 compares $V_{contralateral}$ after iohexol and normal saline. In awake patients, significant increases in $V_{contralateral}$ were observed following iohexol. We observed no such increase in the child having angiography under general anaesthesia; however, the $V_{iohexol}$ increased to 156% between 4 and 8 s after T_0, resembling $V_{iohexol}$ in awake patients.

To single out the *specific responses* which occurred exclusively in the recipient vascular system, and to differentiate these from the *general responses* which occurred in the contralateral hemisphere as well, an index ($V_{relative}$) was calculated by dividing the MCA blood velocity in the hemisphere tested ($V_{iohexol}$ or V_{NaCl}) by the MCA blood velocity on the opposite side ($V_{contralateral}$). After iohexol this index ($V_{relative}$) was significantly decreased in the < 4 s period (mean value 92%) and significantly increased between 4 and 12 s (Fig. 5). A small decrease was observed between 30 and 45 s. Following normal saline, $V_{relative}$ was significantly increased < 4 s after T_0 (mean value 111%) and decreased between 4 and 60 s.

Concurrent Recording of MCA and ICA Blood Velocity

There was significant positive correlation between the relative variations in ICA and MCA blood velocity (V_{ICA} and V_{MCA}) of the recipient hemisphere during injection of iohexol ($r = 0.871$) and normal saline ($r = 0.824$). The least square regression line for V_{MCA} on V_{ICA} was for iohexol $Y = (8.9 \pm 6.0) + (0.95 \pm 0.06)\,X$ (estimate ± standard error), $n = 82$, and for normal saline $Y = (7.3 \pm 8.9) + (0.93 \pm 0.09)\,X$, $n = 48$. For the combined data ($n = 130$) the regression line was $Y = (4.6 \pm 4.9) + (0.98 \pm 0.05)\,x$, $r = 0.869$. Since the cerebral responses to iohexol and normal saline persisted no longer than 60 s, we analyzed separately the data obtained within the first 60 s after T_0 ($n = 84$). The resulting regression line was $Y = (-2.0 \pm 5.2) + (1.05 \pm 0.05)X$, $r = 0.908$ (Fig. 6). The regression lines had slopes not significantly different

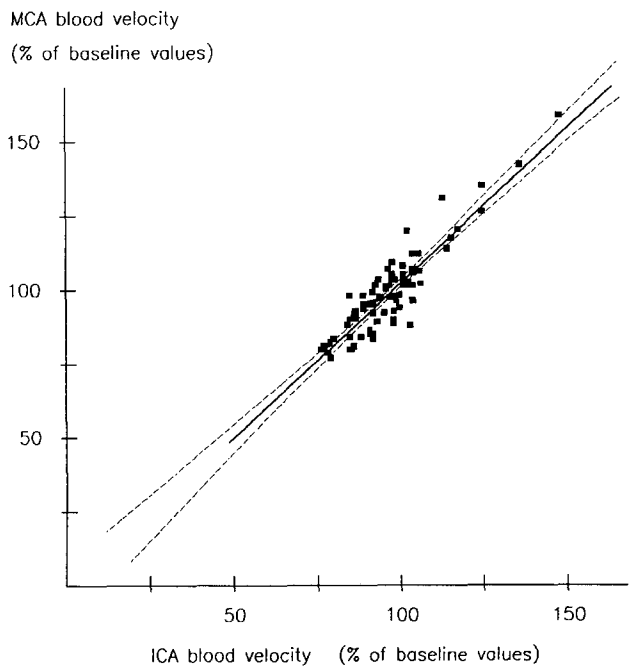

Fig. 6. Least square linear regression analysis of concurrent variations in ICA and MCA blood velocity (V_{ICA} and V_{MCA}) of the recipient hemisphere during iohexol angiography and normal saline injection. The regression line can be described by the equation: $Y = (-2.0 \pm 5.2) + (1.05 \pm 0.05)X$ with the correlation coefficient $r = 0.908$. Broken lines indicate the 95% confidence interval. Broken lines indicate the 95% confidence interval. The slope is not significantly different from 1, and the Y-axis intercept (the estimated value for V_{MCA} given $V_{ICA} = 0$) is not significantly different from 0

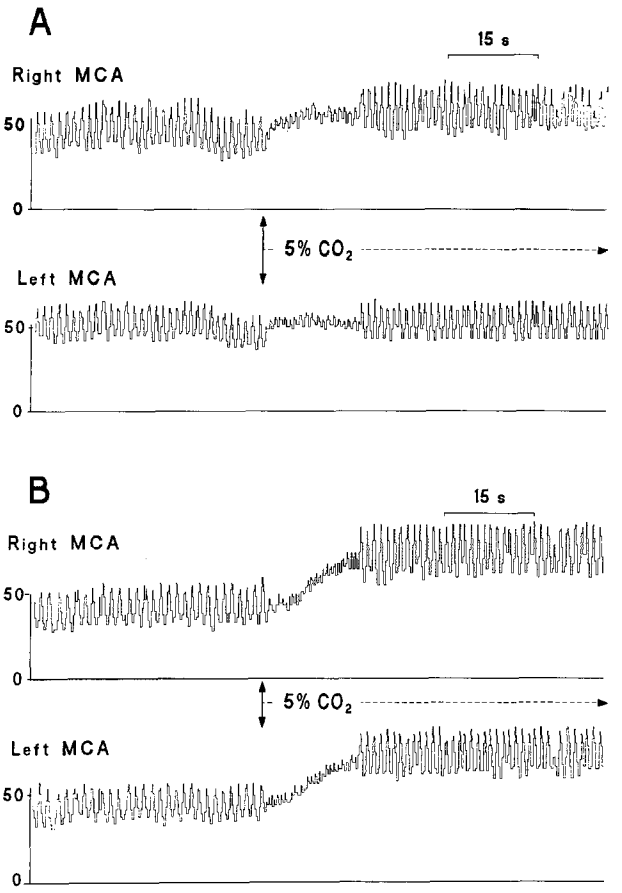

Fig. 7. Male, 70 years, stenosis 90% left internal carotid artery, sporadic transient ischaemic attacks. Concurrent blood velocity recordings from the right (upper) and the left (lower) MCA during two separate preoperative investigations of vaso-reactivity employing inhalation of 5% CO_2. When switching to 5% CO_2, the recording was compressed until a new steady state pCO_2 was reached after about two minutes. The following increases in blood velocities were recorded: Investigation A: Right MCA 19%, Left MCA 1%; Investigation B: Right MCA 54%, left MCA 41%. Thus, there were markedly different responses to this seemingly standardized stimulation. Nevertheless, the response asymmetry persisted

from 1, and Y-axis intercepts (the estimated for V_{MCA} given $V_{ICA} = 0$) not significantly different from 0.

Discussion

Awake patients undergoing arterial catheterization and angiography are prone to anxiety and are certainly in no resting state[3]. We have therefore used the term "baseline" to describe the situation which serves as the point of departure in the present study. The exposure of the brain to an injected substance triggers further complex reactions. When discussing the haemodynamic responses it therefore seemed helpful to distingiush between the *specific respones* in the recipient vascular bed, and the *general responses* occurring in the remote brain areas as well.

General Responses

There was no angiographic evidence of contrast flow into the oppsite MCA. It therefore seems unlikely that iohexol per se caused the changes seen in $V_{contralateral}$. The following explanation seems more plausible. The passage of an angiographic bolus causes burning sensation and pain[17,26]. Anxiety and pain increase cerebral blood flow[3,6]. Pain or discomfort probably elicited augmentations in $V_{contralateral}$ as well as in $V_{iohexol}$ in the awake patients. As the contrast related pain faded, the bolus related general responses also waned. General responses seemed to be absent during angiography under general anaesthesia (Fig. 4.). Normal saline produced no discomfort or pain and hence, no bolus related general response (Figs. 3 and 4).

Specific Responses

The specific responses to iohexol angiography and normal saline injections were biphasic, reciprocal, and with switching between phases about 5 s after injection (Fig. 5). Thus, explanations involving cooling, microembolism, and transiently reduced contents of glucose and oxygen can probably be rejected.

Morris *et al.* injected normal saline into renal arteries in dogs, and observed a brief flow increase followed by a decrease lasting from about 10 s to about 40 s[15,16]. When the bolus viscocity was increased by adding polyvinyl pyrrolidone to normal saline, the initial response was one of decreased flow, whereafter some flow decrease persisted[16]. These experimental findings parallel the present clinical observations. Iohexol has a viscocity of about twice that of whole blood[4]. Thus, when iohexol temporarily and more or less completely replaces blood in arterioles and capillaries, the vascular resistance increases due to a higher viscous drag. The blood velocity drop observed < 4 seconds after iohexol probably reflects the resulting transient flow drop. Conversely, diluting blood with normal saline reduces viscous drag and increases flow and flow velocity. This initial phase of the specific responses seemed to last as long as the normal transit time of contrast from arteries into veins. Therefore, although the role of rapid vasomotor responses[1] are difficult to delineate, the specific responses observed within the first 4 s seem mainly to reflect the different fluid mechanical behaviour of whole blood, iohexol, and normal saline.

Intracarotid injections of hyperosmolar solutions in animals induce transient osmolality dependent increases in cerebral blood flow[14,25]. Thus, phase two of the specific response to iohexol (Fig. 5) was probably due to the high osmolality, about twice of whole blood[4]. Experimental studies seem to confirm that this second phase is less dependent on viscocity[16]. Decreased blood velocities between 4 and 60 seconds after normal saline may reflect vasomotor regulation triggered by the initial flow peak (Figs. 3 and 5). Normal saline is nevertheless devoid of potassium, calcium, and other ions. Such deviations in ion content could have vasoactive effects of their own[24].

Comparable Contrast Media Studies

Nornes recorded ICA blood flow bilaterally in awake patients during cerebral angiography with meglumine-Ca-metrizoate and observed increased blood flow to both hemispheres[19]. Tindall *et al.* recorded carotid blood flow in anaesthetized patients during selective carotid angiography with sodium diatrizoate[23]. The average flow increase was 40% and the flow zenith occurred after 20 s. Stoeter *et al.*[21] measured blood velocity in the common carotid artery while injecting sodium ioxaglate into the ICA in awake patients. The bolus was hence injected downstream to the recording site; nevertheless, following the brief initial drop the blood velocity increased for up to 20 seconds. The same group also measured end-diastolic MCA blood velocity in the recipient hemisphere during test injections with iopamidol[22]. After the brief initial drop, they observed a MCA blood velocity increase of about 25%, and usually lasting 7–8 heart cycles. In experimental iohexol coronary angiography, after the initial drop, coronary blood flow increased to above control levels, reaching a zenith after about 10 seconds[2]. This pattern strongly resembles the specific response to iohexol observed in the present series (Fig. 5).

Do Artery Calibres Change During Cerebral Angiography?

The MCA blood velocity responses to injections of iohexol and normal saline correspond to observations of blood flow in clinical and experimental angiography. Nevertheless, one should not be blind to the possibility that the MCA calibre may change in the settings presently investigated. However, least square linear regression analysis of concurrent relative variations in V_{ICA} and V_{MCA} during iohexol and saline injections revealed a regression line not significantly different from the line of identity (Fig. 6). This implies no significant change in the calibre of the MCA and the ICA, or, alternatively, that any changes were strictly equivalent. The latter possibility seems less probable. Huber and Handa[5] used a magnification method to measure the vessel diameters from angiograms. They found no change for vessels > 2 mm including the proximal MCA and the extracranial ICA, during and 30 seconds after contrast injections, and 30 seconds after injections of normal saline. Moreover, in patients having undergone carotid surgery, a near linear relationship close to unity was observed between the relative variations in MCA blood velocity and ICA blood flow during rapid fluctuations in ICA blood flow[11]. However, to finally determine if the calibre of the human basal cerebral arteries change during angiography it may be necessary to measure blood flow and velocity in these vessels simultaneously, or, alternatively, to obtain very high resolutions images of these vessels during the period of interest.

Clinical Aspects

The main advantage of the present method is to permit noninvasive monitoring of the cerebral circulation at two points of observation at the same time. Thus, recording at two levels along one inflow channel (ICA and MCA) during carotid injections, it allowed analysis of possible site specific effects. However, the main application may be investigations of two separate vascular beds, such as both MCAs, at the same time. In the present study we could separate the *specific responses* to stimuli with direct regional effects and the *general responses* occurring in remote brain as well. The responses in two vascular beds to one acute systemic stimulus may also be assessed. Studies in preparation suggest that, for reasons yet to be defined, repeated seemingly standardized stimulation of the very same vascular bed (breathing 5% CO_2) does not necessarily produce indentical responses. This is illustrated by findings in a patient with severe unilateral ICA stenosis (Fig. 7). The investigation of the haemodynamic responses in two vascular beds at the same time may thus facilitate the assessment of possible regional differences.

The present study has demonstrated the importance of investigating the behaviour of the blood flow in two cerebral arteries at the same time. The concept of two vessel monitoring seems promising for the investigation of cerebral haemodynamics. Its widespread use will, however, depend upon the commercial availability of this option.

References

1. Aaslid R, Lindegaard K-F, Sorteberg W, Nornes H (1989) Cerebral autoregulation dynamics in humans. Stroke 20: 45–52
2. Friedman HZ, DeBoe SF, McGillem MJ, Mancini GBJ (1987) Immediate effects of graded ionic and nonionic contrast injections on coronary blood flow and myocardial function. Implications for digital coronary angiography. Invest Radiol 22: 722–727
3. Gur RC, Gur RE, Resnick SM, Skolnick BE, Alavi A, Reivich M (1987) The effect of anxiety on cortical cerebral blood flow and metabolism. J Cereb Blood Flow Metab 7: 173–177
4. Haavaldsen J (1980) Introduction. In: Lindgren E (ed) Iohexol, a non-ionic contrast medium: pharmacology and toxicology. Acta Radiol [Suppl] 362: 10–11
5. Huber P, Handa J (1987) Effect of contrast material, hypercapnia, hyperventilation, hypertonic glucose and papaverine on the diameter of the cerebral arteries. Angiographic determination in man. Invest Radiol 2: 17–32
6. Lassen NA, Ingvar DH, Skinhøy E (1978) Brain function and blood flow. Sci Am 239: 50–59
7. Lindegaard K-F, Bakke SJ, Grip A, Nornes H (1984) Pulsed Doppler techniques for measuring instantaneous maximum and mean flow velocities in carotid arteries. Ultrasound Med Biol 10: 419–426
8. Lindegaard K-F, Bakke SJ, Grolimund P, Aaslid R, Huber P, Nornes H (1985) Assessment of intracranial hemodynamics in carotid artery disease by transcranial Doppler ultrasound. J Neurosurg 63: 890–898
9. Lindegaard K-F, Bakke SJ, Sorteberg W, Nakstad P, Nornes H (1987) A non-invasive Doppler ultrasound method for the evaluation of patients with subarachnoid hemorrhage. Acta Radiol [Suppl] 369: 96–98
10. Lindegaard K-F, Grolimund P, Aaslid R, Nornes H (1986) Evaluation of cerebral AVM's using transcranial Doppler ultrasound. J Neurosurg 65: 335–344
11. Lindegaard K-F, Lundar T, Wiberg J, Sjøberg D, Aaslid R, Nornes H (1987) Variations in middle cerebral artery blood flow investigated with noninvasive transcranial blood velocity measurements. Stroke 18: 1025–1030
12. Lindegaard K-F, Nornes H, Bakke SJ, Sorteberg W, Nakstad P (1989) Cerebral vasospasm diagnosis by means of angiography and blood velocity measurements. Acta Neurochir (Wien) 100: 12–24
13. Lundar T, Lindegaard K-F, Nornes H (1990) Continuous monitoring of middle cerebral artery blood velocity in clinical neurosurgery. Acta Neurochir (Wien) 102: 85–90
14. Morris TW, Francis M, Fischer HW (1979) A comparison of the cardiovascular responses to carotid injections of ionic and nonionic contrast media. Invest Radiol 14: 217–223
15. Morris TW, Katzberg RW, Fischer HW (1978) A comparison of the hemodynamic responses to metrizamide and meglumine/sodium diatrizoate in canine renal arteriography. Invest Radiol 13: 74–78
16. Morris TW, Kern MA; Katzberg RW (1982) The effects of media viscosity on hemodynamics in selective arteriography. Invest Radiol 17: 70–76
17. Nakstad P, Sortland O, Aaserud O, Lundervold A (1982) Cerebral angiography with the non-ionic water-soluble contrast medium iohexol and meglumine-Ca-metrizoate. A randomized double blind parallel study in man. Neuroradiology 23: 199–202
18. Nornes H (1973) The role of the circle of Willis in graded occlusion of the internal carotid artery in man. Acta Neurochir (Wien) 28: 165–177
19. Nornes H (1977) Internal carotid artery blood flow during cerebral angiography. Neuroradiology 12: 219–225
20. Padayachee ST, Parsons S, Theobald R, Linley J, Gosling RG, Deverall PB (1987) The detection of microemboli in the middle cerebral artery during cardiopulmonary bypass: a transcranial Doppler ultrasound investigation using membrane and bubble oxygenators. Ann Thorac Surg 44: 298–302
21. Stoeter P, Prey N, Hofmann C, Büdingen HJ, Bergleiter (1984) Doppler-sonographic examination of the arterial flow in the carotid and supratrochlear arteries during carotid angiography. Neuroradiology 26: 199–207
22. Stoeter P, Prey N, Scholl-Latour R, Vögele H, Büdingen HJ (1987) Transcranial Doppler monitoring of blood flow in the middle cerebral artery during angiography and drug perfusion. Acta Radiol [Suppl] 369: 103–106
23. Tindall GT, Greenfield JC, Dillingham W, Lee JF (1965) Effect of 50 per cent sodium diatrizoate (Hypaque) on blood flow in the internal carotid artery of man. Am Heart J 69: 215–219

24. Toda N (1978) Mechanical responses of isolated dog cerebral arteries to reduction of external K, Na, and Cl. Am J Physiol 234: H 404–H 411

25. Ulano HB, Asciano G, Rice V, O'Hern R, Houmas E, Oppenheimer MJ (1970) Effects of angiographic contrast media and hypertonic saline solutions on cerebral venous outflow in autoregulating brains. Invest Radiol 5: 518–533

26. Valk J, Crezée F, Olislagers-de Slegte RGM (1984) Comparison of iohexol 300 mg I/ml and Hexabrix 320 mg I/ml in central angiography. Neuroradiology 26: 217–221

Correspondence: Wilhelm Sorteberg, M.D., Department of Neurosurgery, Rikshospitalet, N-0027 Oslo 1, Norway.

Reprints: Prof. Helge Nornes, Department of Neurosurgery, Rikshospitalet, N-0027 Oslo 1, Norway.