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Summary Arterial diameter, blood velocity and blood flow of both common carotid arteries were studied in 24 patients with isolated unilateral internal carotid artery stenosis, without any other significant lesion of the carotid system. The methodology used a pulsed Doppler system with two original characteristics: an adjustable range-gated system and a double transducer probe enabling both the arterial diameter and blood velocity to be evaluated. On the involved side, the diameter, the blood velocity and the blood flow were significantly reduced \((p < 0.001)\) in comparison with the opposite side. The degree of the internal carotid artery stenosis judged on arteriography was negatively correlated with (i) the blood flow of the common carotid artery homolateral to the stenosis \((r = -0.78, p < 0.001)\), and (ii) the ratio of the common carotid artery blood flow between the involved and the opposite side \((r = -0.80, p < 0.001)\). The proposed quantitative evaluation can be suitable for the detection and for the follow up of patients with stenosis of the internal carotid artery who do not have any other lesion of the carotid system.

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THE PRESENT PAPER describes a safe non invasive quantitative method to measure the diameter, blood velocity and blood flow of the common carotid by using an original pulsed Doppler system previously evaluated\(^1\): such a technique was used for the study of patient with unilateral internal carotid artery stenosis in order to obtain quantitative informations about the degree of stenosis and its consequences on the upstream carotid circulation.

Material and Methods

Patients

The study was performed on 24 patients with unilateral internal carotid artery stenosis. The group consisted of 19 males and 5 females with a mean age of 57 ± 8 (± 2 standard error of the mean) years (age range between 45 and 75 years). All treatment was discontinued at least 15 days before the study. 15 patients presented a carotid bruit, 9 patients had had a transient ischemic attack, 7 patients suffered from ischemic heart disease and 2 from arteritis obliterans of the lower limbs. No relation was found between the number of cardiovascular signs and symptoms and the severity of the carotid disease.

Arteriographic Methods

A bilateral carotid arteriography with at least two multiple views of the cervical and intracranial carotid artery circulation was used to establish the diagnosis of unilateral internal carotid artery stenosis. Among the 24 cases, only 8 were studied with selective common carotid artery injection and full intracranial runs, while the 16 remaining had either arch injections or selective carotid injection without full head runs. In all cases, the arteriographic technique used enabled to state that no patient had any stenosis of the common and/or external carotid artery on the side of the stenosis nor any contralateral carotid stenosis. In addition patients with stenosis of the major intracranial arteries were excluded from the study. In contrast, the majority of patients had not adequate arteriographic techniques to make a statement about the intracranial pathways that provided the major collateral circulation to the hemisphere distal to the internal carotid artery stenosis.

The arteriographic measurements of the carotid arterial diameters were carefully performed at 3 points on the arteriogram on the side of the carotid stenosis: in the common artery three centimeters before the bifurcation, in the internal carotid artery at the narrowest part of the stenosis, and in the internal carotid artery at its normal post-stenotic part (fig. 1).\(^3\) The percent of arterial diameter stenosis of the internal carotid artery was calculated as the ratio between the narrowest diameter at the point of stenosis measured on any view of the internal carotid artery and the diameter of the normal post-stenotic part of the artery multiplied by 100 (fig. 1)). For this, the evaluation was performed by two physicians different from the investigator responsible for the carotid blood flow measurements. The two physicians worked in a double-blind study with a reproducibility of 5%. Only vessels demonstrating 40% diameter stenosis or greater were included in the study.

Description of the Pulsed Doppler System

The apparatus used has a frequency of 8 MHZ and two original characteristics: (i) a transducer system with double crystals set at a fixed angle of 120° to each other, providing a bidimensional flow velocity measurement, and (ii) an adjustable range-gated system with pulsed emission.\(^1,2\) Figure 1 shows that, when the
velocity signals recorded from each transducer are equal in absolute value, the angle between the ultrasonic beam emitted by each transducer and the vessel axis equal to half of transducer angle that is to say 60°: the crossing of the common carotid arterial lumen by a small measurement volume is schematized along the ultrasound beam of one transducer.

The electrocardiogram initiates a step advance so that if N is half of the ECG peak numbers between the first and the last velocity signals simultaneously recorded (fig. 2) the arterial diameter is calculated as: 
$$D = 0.4 \text{ mm} \times N \times \sin 60°$$
the ultrasound beam incidence angle with the vessel axis; the accuracy is again confirmed in this study by the existence of significant correlation between the common carotid artery diameter measured by arteriography and that calculated by the pulsed Doppler methods in all the patients ($r = 0.77; p < 0.001$). Once the arterial diameter is determined, the cross-sectional velocity of the artery (V) is obtained by increasing the width of the measurement volume up to the diameter value and superimposing it on the arterial lumen. Then, the mean arterial volumetric flow of the artery (Q) is deduced according to the formula
$$Q = \pi D^2/4 \cdot V_m \cdot 60$$
where D is the arterial diameter and $V_m$ the mean arterial velocity calculated by electronic integration of the instantaneous cross-sectional velocity of the artery. Arterial diameter is expressed in cm, and arterial flow velocity and volumetric flow are expressed in cm/sec and ml/min.

In clinical practice, after a rest period of 20 minutes, measurements were made with the patient unsedated and in the supine position; the head was tilted backward, the examination was done in a quiet and semidarkened room, at a constant temperature of 20°C. The position of the carotid artery was determined by palpation along the medial edge of the sterno-cleidomastoid muscle. After the carotid bifurcation has been located by continuous wave Doppler assessment, the pulsed Doppler probe was placed on the common carotid artery 3 cm proximal to the carotid bifurcation. The common carotid artery was chosen rather than the internal carotid artery for the study, because it is not always possible to distinguish accurately with the Doppler system the internal carotid artery from the external carotid artery. Also, concerning the probe transducer incidence angle, the precision of the axis of the common carotid artery in the neck is fairly constant, while the configurations of the internal and external carotids give a high degree of variability. An ultrasonic gel was used as a coupling medium between the probe and the skin. The Doppler signals were monitored by a loud speaker throughout the examination. The velocity signals were recorded on a Siemens apparatus and all measurements of diameter and blood flow velocity were repeated at least twice for each common carotid artery and the value used was the mean of these determinations. Total duration of the study was about 30 minutes for each patient. The reproducibility was 95% for the apparent Doppler diameter and 97% for the mean velocity. The normal values obtained in our laboratory in intact subjects between 45 and 75 years were 0.653 ± 0.011 (SEM) cm (range from 0.560 to
0.780 cm) for diameter, 19.4 ± 1.0 (SEM) cm/sec (range from 15 to 31 cm/sec) for blood velocity, and 380 ± 15 (SEM) ml/min (range from 250 to 520 ml/min) for blood flow.4,5 These values did not show any significant difference between the right and the left side and were in agreement with the previous published data of the literature.5-9

The protocol was approved by I.N.S.E.R.M. (Institut National de la Santé et de la Recherche Médicale); consent for investigation was obtained in all cases after a detailed description of the procedure.

Statistical Analysis

Statistical analysis was performed according to standard methods.10 Differences in means were assessed by the student's t test. A p value of less than 0.05 was accepted as being statistically significant.

Results

Figure 3 summarizes the individual arterial parameters in patients with internal carotid artery stenosis. On the uninvolved side, the mean values of arterial diameter, blood velocity and blood flow were within the normal range for our laboratory. Only one patient had a value of blood flow above the upper limit of our normal values (see methods). In comparison with the uninvolved side, the involved side exhibited a significant reduction in arterial diameter, blood velocity and blood flow (p < 0.001).

Figure 4 indicates the values of the common carotid artery blood flow of the involved side, as a function of the degree of diameter stenosis judged on the arteriography. From 40 to 80% degree of diameter stenosis, blood flow was reduced (mean value: 250 ml/min) and remained nearly constant. After 80% of diameter stenosis, blood flow decreased abruptly. A strong negatively curvilinear relationship (r = -0.78; p < 0.001) resulted from this hemodynamic pattern. A similar correlation (r = -0.70) was observed when blood velocity was used instead of blood flow. No significant correlation was noted between the arterial diameter and the degree of internal carotid artery stenosis.

Figure 5 shows the relationship between the degree of internal carotid artery stenosis and the ratio between the common carotid blood flow of the involved side and the blood flow of the opposite side. The relationship was linear with a correlation coefficient of r = -0.80 (p < 0.001). A similar correlation was observed with blood velocity (r = -0.74), but not with arterial diameter. From figure 5 it appears clearly that an 80% degree of stenosis corresponds to a 50% ratio of flows.

Discussion

Pulsed Doppler techniques permit an accurate non-invasive method of measurement of carotid artery blood flow.6-9,11 The bidimensional pulsed Doppler...
system used in this study, enables one to measure diameter, velocity and blood flow of the common carotid artery; its validation has been largely discussed elsewhere, and the diameter values of the common carotid artery obtained in our laboratory are in perfect agreement with the listing of other authors, and have correlated well with the measurements obtained on the arteriogram.

The main finding of this work is that the common carotid artery blood flow proximal to a unilateral internal carotid artery stenosis of 80% or more, was significantly lower than the contralateral common carotid artery flow; such a reduction is of approximately 50% magnitude. Similar results were found in the literature for patients with severe stenosis or occlusion of the extracranial portion of the internal carotid artery. The common carotid artery flow reduction upstream to the internal carotid artery stenosis questions the arterial pathway of the collateral flow to the cerebral hemisphere distal to the stenosis. The possibilities exist that the external carotid artery ipsilateral to the stenosis might act as suppliers of the collateral flow via the ophthalmic artery, the contralateral internal carotid artery, and/or the vertebral circulation. Unfortunately the arteriographic technique used in this study does not provide adequate information on collateral pathways especially for the intracranial circulation and does not allow us to discriminate the respective role of the former possibilities in the collateral circulation. However the observation of a reduced flow in the ipsilateral upstream common carotid artery might suggest that the ipsilateral carotid system does not supply the ipsilateral hemisphere and that the contralateral carotid and/or posterior circulation ensure the major collateral flow. Such an hypothesis is also consistent with the increase in flow above the normal values in the contralateral carotid artery reported after acute digital compression of one common carotid artery in normal subjects, but the common carotid blood flow contralateral to the internal carotid artery stenosis was normal rather than increased in this study and in other reports. This seems to indicate that compensatory flow mechanisms in the carotid circulation are different in acute and in chronic conditions.

Another important finding of this work was to observe that the decrease in common carotid artery blood flow as due both to a reduction of blood velocity and to arterial diameter of the artery. Indeed, blood flow was calculated as the product between blood velocity and cross-sectional area of the artery. The reduction of the blood velocity could easily be explained on the basis of increased internal carotid artery resistance consequent to the existence of a down-stream stenosis of this artery. The diameter reduction is more difficult to interpret. The caliber reduction was not correlated with the degree of the internal carotid artery stenosis, as were blood flow and blood velocity.

Lastly, when the degree of internal carotid artery stenosis was correlated with the ratio between ipsilateral common carotid artery blood flow to that in the contralateral common carotid artery a strong linear correlation was observed (fig. 5). This finding suggests that this common carotid flow ratio could be used to evaluate the degree of internal carotid artery stenosis; such an evaluation is of prognostic interest because the degree of internal carotid artery stenosis seems to have a great importance in the incidence of strokes.

However, this technique for using common carotid flow data to interpollate internal carotid artery is applicable only when no other significant arterial lesions are present.

References

Pulsed Doppler: an evaluation of diameter, blood velocity and blood flow of the common carotid artery in patients with isolated unilateral stenosis of the internal carotid artery.

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