Noninvasive Measurement of Velocity Profiles and Blood Flow in the Common Carotid Artery by Pulsed Doppler Ultrasound

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SUMMARY  A computer-controlled 14-channel pulsed Doppler ultrasound instrument was used as a noninvasive means to evaluate instantaneous velocity profiles and flow in the common carotid arteries of 22 healthy persons and in 22 patients. Of the latter, 13 had severe obstructions of the extracranial portion of the carotid artery, four had obstruction of the intracranial portion, and five had severe aortic valve insufficiency (AI), with more than 60% regurgitation in all cases. Measurements could be performed within an accuracy of about ± 20% under clinical conditions and revealed perfusion values of 5 to 8 ml per second (300 to 480 ml per minute) in healthy persons. Of the patients, values less than 3 ml per second (180 ml per minute) were detected in nine, between 3 and 5 ml per second (180 to 300 ml per minute) in four, and normal values in another four, while significant backflow was observed only in patients with severe AI. Consecutive blood flow profiles were recorded every 4 msec; these demonstrated that, for a period lasting from 40 msec to 280 msec after the initial systolic peak, blood flow decelerated more rapidly in the central portion of the vessel lumen than near the wall. This situation was present in all healthy persons and in most patients with pathological flow. In patients with AI, flow reinversion from reverse to normal began near the vessel wall, while in the middle third of the vessel lumen, blood was still flowing backward. These phenomena seem to be in agreement with the theoretical and experimental findings of Wernersky, Müller, and others. The AI patients who underwent artificial valve implantation were studied ten days after operation and showed no or little backflow in the common carotid artery at that time.

Introduction

MOST DOPPLER ULTRASOUND devices (continuous-wave and pulsed) yield semiquantitative information on instantaneous velocity and flow rate in a blood vessel, but the data obtained are not sufficiently accurate to evaluate the vascular patient. The use of commercially available Doppler continuous-wave devices to assess obstructions in extracranial cerebral arteries is promising, particularly when additional maneuvers such as compression tests are performed. Procedures using pulsed velocity meters with only a single channel are generally too time consuming for clinical screening of at-risk patients. In this paper we present a multichannel computer-assisted pulsed Doppler ultrasonic system and its application in the quantitative evaluation of cerebrovascular insufficiency in the presence of carotid artery obstructions. The system provides information in terms of absolute values for the instantaneous velocity and flow rate in centimeters per second and milliliters per second within an accuracy of about ± 20%. The ultrasound device was developed at the Institute of Biomedical Engineering of the University of Ziirich and the Federal Institute of Technology. Modifications required for computer control were carried out in the Neurological Department of the Kantonsspital Ziirich. The instrument supplements a bidirectional continuous-wave Doppler apparatus described in previous papers. The pulsed system is used either prior or subsequent to the continuous-wave Doppler examination of carotid and vertebral artery perfusion by switching from one system to the other.

Technical System

14-Channel Pulsed Doppler Instrument

The 14-channel pulsed Doppler instrument consists of emitter/receiver, timer, gate circuitry, gate selector, and demultiplexer. A vessel is located using stereo-earphones and depth-diameter selector (fig. 1). A short burst of ultrasound (eight sine waves of 7.3 Megahertz) is emitted every 40 microseconds from the piezo-electric transducer in the probe, passing into the tissue and across a blood vessel. Echoes from tissue structures and moving erythrocytes return to the transducer with a time delay proportional to the range. The echo from a desired observation range is then selected by range gating of the return signal. To do this, a timing circuit opens the sample gate for a short period after a selected time interval. By increasing the time interval one selects a greater depth of observation, and vice versa. By increasing or decreasing the gate period (period of sampling) one increases or decreases the range of observation. Energy loss due to attenuation and spherical scattering is compensated by a special gain-function amplifier allowing the velocity in a vessel to be determined independently from its depth, within limits.

Resolution or the ability to separate adjacent target streamlines is approximately 0.5 mm. The Doppler shift frequency is calculated simultaneously for 14 target streamlines within the range of observation. Thus, the instantaneous velocity of 14 individual streamlines, placed at uniform intervals across the vessel, is provided by the gate circuitry. By externally triggering the gate selector and demultiplexer, the instantaneous velocity for each streamline can be read out of the gate circuitry. Spatial profiles are synthesized by linear interpolation between adjacent streamlines, and the flow rate is calculated from the mean flow velocity times the cross-sectional area of the vessel. This area is determined when the range covered by the set of gates corresponds to the distance between the...
proximal and distal vessel walls. The vessel is assumed to have a circular cross-section, and the vessel diameter is determined by correcting for the 45° angle of the probe relative to the vessel axis.

The Function of the Pulsed Doppler System

The system consists of the 14-channel Doppler instrument, the remote control unit, and the data processor (fig. 1). Measurements are performed with the patient in a supine position. The probe is hand-held or mounted on a mechanical stage from a microscope, which is fixed to a flexible arm, and is placed over the target vessel with an angle of approximately 45° between probe and vessel axis. Aquasonic 2,000 ointment serves for impedance adaptation between skin and ultrasound crystal.

The ECG of the patient triggers both the PDP-12 digital computer and the oscilloscope displaying instantaneous velocity and flow rate. Every 4 msec, pulses of the computer's digital-to-analog (DA) converter reset both the Doppler device and a second oscilloscope which shows the instantaneous profiles. Within 500 microseconds, velocity values of the 14 individual streamlines held in the 14-gate circuitry are sampled and read into the DA-converter of the computer by consecutive pulses of the DA-converter. In this way, flow alterations along and transverse to the vessel axis up to a frequency of about 100 Hz can be detected. Up to eight proximal or distal gates can be omitted as desired. Thus, 6 to 14 streamlines can be selected and analyzed, and range gating can be performed on a vessel varying in diameter from 3 to 18 mm, with the proximal vessel wall 1 to 20 mm deep to the surface, assuming an angle of 45° between probe and vessel axis.

Consecutive instantaneous profiles and the audio signals from the most proximal and distal streamlines are used to set the depth and range covered by the gates with the aid of the depth-and-diameter selector. Instantaneous velocity and flow rate in the vessel (circular cross-section assumed) are displayed on the particular oscilloscope and recorded continuously together with the superimposed R-peak of the ECG on two channels of the recorder. On commands
transmitted by footswitches, the computer begins averaging the information of each streamline over 20 cardiac cycles. The averaged results (instantaneous velocity and flow rate in the vessel as a whole, individual streamlines, and consecutive profiles) appear immediately on an oscilloscope and can be stored on digital tape for recall and further comparison. All functions of the system and computer programs are controlled by footswitches during an examination, thus leaving both hands free for probe placement and adjustment maneuvers.

Methods and Patient Material

The validity of the pulsed Doppler instrument was tested by Rutishauser et al. in a previous series of experiments on the surgically exposed thoracic aorta of 11 dogs. Results of flow rate and velocity were compared with simultaneous electromagnetic flowmeter measurements. Flow rate values corresponded with a correlation coefficient of 0.93. Under electromagnetic flowmeter measurements. Flow rate values gained with more precise methods using electromagnetic flowmeters and the beaker-and-stopwatch method.

Our pulsed Doppler system was calibrated in vivo by comparing Doppler measurements with electromagnetic flow measurements. Eighty-seven measurements over 20 cardiac cycles on ten different arteries of two dogs were performed (both common carotid arteries, abdominal aorta, and both common iliac arteries) with the probe placed directly on the surgically exposed vessel and repeated with 0.5 to 1.5 cm tissue interposed between probe and vessel. Outer vessel diameter varied from 4 to 12 mm.

The conclusion that the profiles gained with our system were real was drawn from the following considerations: If the flow rate calculated from vessel diameter and velocity profiles measured with our instrument does not deviate from flow rate values measured with independent and well-established methods such as electromagnetic flowmeter measurements or the beaker-and-stopwatch method, it is unlikely that the demonstrated velocity profiles do not correspond to the real profiles.

Of the extracranial cerebral arteries only the common carotid can be studied satisfactorily with our present percutaneous techniques. The reason is twofold: First, it is not always possible to distinguish by the probe which branch is internal carotid and which is external carotid. Second, while the axis of the common carotid artery in the neck is fairly constant, there is a high degree of variability in the configuration of the carotid bifurcation and of the axes of the internal and external carotids. Thus, the reproducible probe-artery angle which is necessary for quantification of blood flow cannot be guaranteed for vessels above the bifurcation.

To generate a “Doppler angiogram” a fully computerized procedure with the probe following automatically along a vessel would be necessary to satisfy the needs of a routine examination. This, however, is beyond the capability of our present system.

The system was used percutaneously over the common carotid arteries of 22 healthy persons, age 23 to 45 years, in 12 patients with severe extracranial stenosis or occlusion of one internal carotid artery, in a 28-year-old patient with coarctation of the thoracic aorta and severe stenoses of origins of the brachiocephalic trunk and the left common carotid artery at the coarctation site, and in four patients with intracranial occlusion in or distal to the carotid siphon. Five patients with aortic valve insufficiency (AI) also underwent examination (the cardiac lesions were demonstrated and quantified by cardiac catheterization).

Angiography and carotid artery Doppler examination of the 12 patients with internal carotid artery obstructions demonstrated that four lesions were bypassed by collateral flow through the circle of Willis (i.e., collateral flow from the opposite internal carotid or the basilar artery), six had reverse flow in the homolateral ophthalmic artery only (external-to-internal carotid anastomosis), without a contribution from the circle of Willis, and no collateral circulation was observed in two patients.

Pulsed Doppler measurements were performed at the same time as carotid and vertebral artery Doppler examination by the continuous-wave system, usually after the continuous-wave examination had been completed.

Results

Calibration Experiments

Calibration experiments using both carotid arteries, abdominal aorta, and both common iliac arteries of two dogs with electromagnetic flowmeters proximal to the probe showed agreement in volume flow rate within ± 20% for inner vessel diameters varying from 3 to 10 mm under “clinical conditions,” i.e., when 0.5 to 1.5 cm tissue was interposed between probe and vessel. The ultrasound probe was mounted on a mechanical stage and was placed in line with the vessel axis, the angle between probe and vessel axis being 45°. Angle measurements were accurate to ± 3°.

Percutaneous Measurements

Percutaneous measurements over the common carotid arteries in persons with normal carotid perfusion showed values between 5 and 9 ml per second (300 to 540 ml per minute) in each vessel, taken as an average over 20 cardiac cycles. Computations of a single mean value with standard deviation for a “standard” carotid artery are not useful, not only because of variations between individuals but also because the error in percutaneous probe placement and nonlinearities of the pulsed Doppler instrument do not justify the use of these parameters (angle and axis may deviate at least ± 5° from ideal values from one examination to the next).

Four patients in the pathological group had flow values within the normal range in the affected artery, another four patients between 3 and 5 ml per second (180 to 300 ml per minute), and nine patients less than 3 ml per second (180 ml per minute). Backflow at some time during diastole was observed only in patients with severe aortic insufficiency (regurgitation more than 60% at cardiac catheterization) and in the patient with a congenital malformation of aorta, brachiocephalic trunk, and left common carotid artery. The flow rate reached zero in a phase of diastole in five patients with internal carotid artery occlusion. For comparison, low diastolic flow due to increased peripheral resistance had
been detected semiquantitatively in nine patients by the continuous-wave carotid artery Doppler done earlier. This finding was used as a diagnostic criterion of carotid artery stenosis. Of these nine patients, six had a flow rate less than 3 ml per second (180 ml per minute) by pulsed Doppler, while two patients fell into the 3 to 5 ml per second (180 to 300 ml per minute) range, and one patient had normal values.

Case Reports

Case 1: Normal Carotid Artery Perfusion

Normal carotid artery perfusion in a healthy 28-year-old person is shown in figure 2. The probe was placed approximately 2 cm proximal to the carotid bifurcation with flow direction toward it. The inner vessel diameter was 5.9 mm. The depth-and-diameter selector was arranged so that all streamlines lay within the vessel lumen. Instantaneous flow and velocity had peak values during systole of 15 ml per second and 45 cm per second, respectively, and were lowest when the aortic valve closed (about 2 ml per second and 7 cm per second). Mean diastolic flow rate was 4.5 ml per second. The 14 individual streamlines were quite steady during the 20 cardiac cycles of recording (maximum SD during systolic peak flow was less than 1 ml per second). Velocity profiles taken every 4 msec were flat from the middle to the end of diastole, developed a parabolic configuration during the systolic acceleration phase, and showed a faster deceleration of blood flow in the middle third of the vessel lumen than near the wall for about 280 msec between late systole and early diastole ("saddle-like" profiles).

Case 2: Right Internal Carotid Artery Occlusion

Right internal carotid artery occlusion was demonstrated by continuous-wave carotid artery Doppler and angiography in a 58-year-old patient with multiple vascular problems including claudication in the right leg, a previous myocardial infarction, amaurosis fugax in the right eye, and a stroke in the right hemisphere (fig. 3). Measurements with the pulsed Doppler system over the right common carotid artery (side of the occluded internal carotid) showed an inner vessel diameter of 6.1 mm, a mean flow rate and velocity of 2.4 ml per second (140 ml per minute) and 8.2 cm per second with systolic peak values of 8 ml per second and 30 cm per second, respectively. Nearly zero flow was observed during the closing phase of the aortic valve, and the mean diastolic flow rate was below 2 ml per second. Velocity profiles did not show a "saddle-like" shape in any phase of the cardiac cycle. The left common carotid artery was 6.9 mm in diameter with a mean flow rate and velocity of 6 ml per second (360 ml per minute) and 15 cm per second and systolic peak values of 15 ml per second and 38 cm per second. The mean diastolic flow rate was 5 ml per second.

Figure 2. Flow conditions in the common carotid artery of a healthy 28-year-old woman (Case 1). Flow is directed toward the brain in all phases of the cardiac cycle and never reaches zero level. Mean flow rate is about 5 ml per second (300 ml per minute), and diastolic mean flow rate is about 4.5 ml per second (270 ml per minute). In the upper portion of the figure, the first graph depicts total flow and velocity in the vessel as a function of time, while the middle graph represents the individual streamlines of which the total flow is composed. SD of the individual streamlines is low (maximum less than 1 ml per second). At the bottom of the figure, sequential velocity profiles across the lumen of the vessel during a cardiac cycle are depicted (average over 20 cardiac cycles). Profiles are taken at 4-msec intervals, and for convenience are displayed side by side in columns of ten profiles each, rather than in one continuous ascending column. Each column of profiles thus represents a 40-msec interval of the cardiac cycle. Profiles are ordered bottom to top, and columns left to right. Velocity profiles, calculated at 4-msec intervals by linear interpolation between adjacent streamlines, show a "saddle-like" contour after the initial systolic peak until early diastole, a period of about 280 msec. This indicates lower flow in the middle third of the vessel lumen compared to values near the wall during this phase of the cardiac cycle.
profiles were "saddle-like" in shape for about 40 msec after the first systolic peak.

Case 3: Severe Aortic Valve Insufficiency

Figure 4 shows the findings in a 28-year-old patient who had severe insufficiency of the aortic valve probably due to bacterial endocarditis. Cardiac catheterization verified approximately 75% regurgitation. Pulsed Doppler examination showed backflow (= backward volume:total forward volume X 100%) of about 35% in all major extracranial cerebral vessels, and was even observed in the ophthalmic arteries. Instantaneous flow rate and velocity had a large second peak in late diastole (possibly due to left atrial contraction), and a sharp deceleration of blood velocity therefore could be detected before the systolic rising phase. Backflow was also demonstrated in the velocity profiles, with a "saddle-like" shape during the diastolic peak. Flow inversion from reverse to normal could be observed starting near the vessel wall, while blood in the middle third of the lumen was still flowing backward. The patient had an implantation of a Bjork-Shiley aortic valve prosthesis. Measurements over the common carotid artery on the tenth postoperative day demonstrated a much lower diastolic peak and only about 4% backflow during the closing phase of the artificial valve. Intracranial backflow, diagnosed by ophthalmic artery measurements, was no longer present.

Discussion

Percutaneous velocity profile determination in the common carotid artery is a step toward noninvasive quantification of blood flow in the major extracranial cerebral vessels. Our instrument allows simultaneous (parallel) recording of 6 to 14 individual streamlines at uniform distance within a vessel. Thus, flow alterations can be demonstrated which

**Figure 3.** Flow conditions in both common carotid arteries of a 58-year-old patient with an occluded right internal carotid artery (Case 2). Mean flow rate on the affected side is less than 3 ml per second (180 ml per minute) with cessation of flow during the closing phase of the aortic valve. Perfusion values of the left common carotid artery are within normal range, and the "saddle" phenomenon is observed for 60 msec after the systolic peak in this vessel. There is no "saddle" phenomenon in the affected right carotid. For brevity, only velocity profiles for the systolic phase of the cardiac cycle are represented.

**Figure 4.** Flow conditions in the right common carotid artery of a 28-year-old patient with severe insufficiency of the aortic valve before and after implantation of a Bjork-Shiley aortic valve prosthesis (Case 3). About 35% backflow with a large diastolic peak is detected before the operation, while only about 4% backflow with a diminished diastolic peak is present afterward. Note that flow direction reverts from reverse to normal first near the vessel wall, during which time backflow is still present in the middle third of the lumen. This effect is more pronounced preoperatively. Before and after the operation mean flow rate is about 3 ml per second (180 ml per minute) compared to a normal range of 5 to 8 ml per second (300 to 480 ml per minute).
right common carotid artery 10 days after operation

Right common carotid artery before operation

Profiles every 4 ms
cannot be visualized by methods based on serial processing of the velocity information in the different streamlines. Profiles can be adequately composed even in unstable cardiac situations.1 7 8 Measurements of flow rate can be performed in approximately ten minutes and with an accuracy of about ± 20% using the present Doppler instrument and probe placement procedure.

In this fashion, normal common carotid artery flow rates in the range from 5 to 8 ml per second (300 to 480 ml per minute) can be distinguished from abnormal values below 3 ml per second (180 ml per minute) in some patients with severe obstructions in the common or internal carotid artery. Normal values correspond to physiological and anatomical findings showing a total brain perfusion of 700 to 950 ml per minute with more than 60% coming from the two internal carotid arteries.19 14 Values between 3 and 5 ml per second (180 to 300 ml per minute) indicate a possible disturbed extracranial perfusion and must be interpreted with caution in view of the measurement error due to inaccurate probe placement. The results are more accurate than the semiquantitative estimate obtained by continuous-wave measurements, in which the vessel diameter is not considered and moving tissue between skin and blood vessel interferes with velocity measurements.

Not every patient with severe internal carotid artery obstruction has a common carotid flow rate in the pathological range. This can be explained either by external carotid artery branches feeding via the ophthalmic, meningeal, or scalp arteries into the intracranial portion of the carotid artery (observed in six patients) without increasing peripheral resistance, or by increased external carotid artery perfusion by some other as yet undefined mechanism ("luxury perfusion").14

Instantaneous velocity and flow curves demonstrate that diastolic flow normally contributes about 80% of the total flow in a carotid artery, and only about 20% is added by the systolic peak.15 16 Low diastolic flow therefore can be used as a diagnostic parameter in situations with increased peripheral resistance due to local stenosis, general diffuse intracranial arteriosclerosis, and increased intracranial pressure. In these situations the flow can reach zero level at some time during the diastolic phase. Pulsed Doppler results therefore can be used to interpret relatively low diastolic flow values detected with the continuous-wave Doppler, at times such low diastolic flow values by continuous-wave Doppler may be due to mechanical artifact (e.g., pronounced lateral movement of a vessel wall). In rare cases low diastolic flow rate in the common carotid artery is the only detectable hemodynamic irregularity in the presence of a stenosis, and pulsed Doppler examination can be especially useful in these patients.8 4

Fast deceleration of blood volume in the middle third of a carotid artery after the systolic peak in normal persons seems to be in agreement with the theoretical and experimental findings of Wormersley.19 Müller,14 and others for a certain range of the "alpha" number for sinusoidal flow in a tube.7 10 17 18 Alpha depends on vessel diameter (2r), frequency (f) of flow alteration, viscosity (μ) and density (γ) of the fluid (α = r V2 f μ γ). Axial migration of blood cells toward the center of a vessel also may contribute to the faster deceleration in the middle third of the vessel lumen, since density alterations affect the spatial flow pattern.14 This "saddle" phenomenon could be observed in both normal and pathological cases, primarily proximal to the carotid bifurcation and over a distance of about 2 cm along the common carotid artery. The phenomenon disappeared outside this area, probably due to a change in the alpha number. The theoretical findings also seem to agree with the phenomenon observed in the patients with severe aortic valve insufficiency, in whom reverse flow changed back to forward flow near the vessel wall, while backflow was still present in the middle third of the lumen.16 20

Significant diastolic backflow was noted only in patients with severe aortic insufficiency with a regurgitation rate of more than 60% from the aorta to the left ventricle. The cerebrovascular system seems to be capable of smoothing out the backflow effect of lower grade cardiac lesions by a decrease in the peripheral resistance. The pulsed Doppler system theoretically allows us to quantify the influence of aortic valve insufficiency on cerebral blood flow. Sequential Doppler studies in patients with moderate AI might decrease or eliminate the need for repeated catheterization to assess progressive clinical deterioration. The hemodynamic effect of aortic valve replacement can be studied quantitatively yet noninvasively with this technique.

A reduction in flow measurement error below the 20% level could be achieved in future systems by combining B-mode and Doppler ultrasound systems, since the former can yield information not only about the structure of the tissue, but also about the spatial relationship between the ultrasound beam and the vessel axis.21 Selective measurements over the initial portion of the internal carotid artery would then become possible. Our method does not yet insure selective placement of the probe over this particular target vessel. Variations in the level of the bifurcation, in the external carotid artery branches in this region, and in the branching direction of the internal carotid itself are considerable, which can often lead to false results with our system if attempts to make readings above the common carotid are made.

Percutaneous velocity profile measurements in addition to continuous-wave examination (carotid and vertebral artery Doppler)4 6 are an aid in the diagnosis of the cerebrovascular patient by noninvasive means. These procedures do not replace angiography, since exact localization of an obstruction is only possible in a small group of patients. However, this may change with Doppler angiography in the near future.18 Until then, these noninvasive procedures facilitate the decision for or against angiography in critical cerebrovascular situations and in evaluation of the undiagnosed patient, for example, the patient with an asymptomatic carotid bruit.14 The methods contribute to clinical follow-up studies of the endarterectomized patient. They may assist in identifying progression of the degree of obstruction in one or several extracranial vessels of the cerebrovascular risk patient before a decapacitating or fatal stroke occurs.

References
The Reliability of Clinical Predictors of Extracranial Artery Disease

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SUMMARY

The records of 628 patients admitted to the Joint Study of Extracranial Arterial Occlusion with transient symptoms of carotid system ischemic disease were examined to determine the accuracy of predicting disease of the extracranial internal carotid artery on the basis of clinical information alone. A patient with a history of episodes of amaurosis fugax is more likely to have a lesion of the internal carotid artery on the same side than if he were having only transient cerebral ischemic attacks.

THE HISTORIES, clinical findings and arteriographical reports on all patients admitted to the Joint Study of Extracranial Arterial Occlusion with transient symptoms of carotid system ischemic disease were examined to determine the extent of extracranial internal carotid artery disease. It has been stated that amaurosis fugax seems to be a highly specific indicator of proximally located carotid lesions, being associated with only 4% of normal internal carotid arteries, as compared to 27% for patients with transient focal cerebral attacks alone. That report was based on findings in 64 patients. We felt that it would be of interest to ascertain whether or not our group of 628 patients in these categories corroborated these statistics (table 1). All patients had arteriography during their initial evaluation.

The figures recorded in table 1 tend to substantiate the report cited. The arteriographical demonstration of a normal ipsilateral carotid artery was only 22% (51 of 234) for patients with amaurosis fugax (with or without associated transient focal cerebral ischemic attacks), but was 43% (168 of 394) in patients with transient focal cerebral ischemic attacks alone. Furthermore, the incidence of an angiographically normal carotid artery was 15%. In those patients with transient symptoms and no palpable pulsation in the cervical region on the appropriate side, the incidence of an angiographically normal carotid artery was zero.
Noninvasive measurement of velocity profiles and blood flow in the common carotid artery by pulsed Doppler ultrasound.
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