SUMMARY  Doppler sonography of 29 extracranial carotid arteries was performed twice within three
days or less. Angiography revealed stenoses with from 10 to 95% diameter reduction in 25 internal carotid
arteries whereas four vessels were found to be normal.

The systolic peak frequency of the internal carotid artery read from the Doppler spectrum (n = 29) could
be reproduced very well. This was shown by a linear regression nearest the line of identical values with a
coefficient of correlation r = 0.97 (p < 0.001). Other values derived from the spectral analysis of the
Doppler shift signal were not so well reproduced including the peak frequency ratio (systolic peak frequency
of the internal carotid artery/systolic peak of the common carotid artery) (n = 22; r = 0.81; p < 0.001). The
mean frequencies read from the zero-crossing detector recordings (n = 20) could not be reproduced as
demonstrated by a linear regression far away from the line of identical measurements with a coefficient of
correlation r = 0.43 (p < 0.05).

DIRECT EXAMINATION of the extracranial carotid arteries by handheld Doppler probes has been well
established in Germany since 1976.18 The same tech-
niques were reported in the United States of America
by Barnes et al.2

Direct Doppler information can be recorded as a
velocity wave-form on a strip chart recorder, which
provides information on the mean frequency of the
Doppler shift throughout the cardiac cycle, or present-
ed as a display of the spectrum of frequencies con-
tained in the Doppler shift signal throughout the cardi-
ac cycle, which allows one to identify actual peak
frequencies. In this report we have examined the repro-
ducibility of the mean frequencies at peak systole, the
actual peak frequency, the ratio of the systolic peak
frequency in the internal to that in the common carotid
arteries and of calculated percent stenosis obtained
from peak systole ratio data.

The best means of documenting Doppler signals is
to photograph Doppler spectral wave forms.14 Spec-
trum analysis of pulsed Doppler signals of the extra-
cranial carotid arteries was first reported by Barnes et
al1 and Felix et al,4 whereas spectra of continuous wave
Doppler signals were obtained some years later by
Lewis et al16 and Reneman and Spencer17 using off-line
techniques.

A few reports have since appeared documenting the
diagnostic accuracy of real time spectral analysis of
continuous wave Doppler signals,3,5,11 especially with
stenoses of up to 50 percent reduction of vessel diam-
eter.4,11,12

However, we have not found any report of the repro-
ducibility of carotid artery Doppler frequency mea-
surements. But when using a diagnostic tool, both
reproducibility and the diagnostic accuracy should be
known, particularly when the patient undergoes opera-
tion of the carotid arteries without angiographic imag-
ing, such as is not uncommonly performed in Ger-

It is the purpose of this study to define the reproduc-
ibility of carotid artery Doppler frequency signals de-
"iving both from a zero-crossing detector and from a
FFT (Fast Fourier Transform) frequency spectrum analy-
iser.

Materials and Methods

We examined 29 carotid arteries of 21 patients twice
within three days or less. In all 21 patients biplane
carotid arteriography had been performed. The Dopp-
ler frequency measurements of 13 extracranial carotid
vessels were not taken into consideration because in
seven patients only unilateral angiography was per-
fomed and because another six patients had contralat-
eral complete occlusion of the internal carotid artery.
In occluded vessels no Doppler shift signal will be
obtained. Angiography revealed stenosis with from 10
to 95% diameter reduction in 25 carotid arteries,
whereas four carotid arteries were found to be normal.

Although peak frequency data in the internal carotid
was available for all 29 internal carotid vessels, peak
frequency data for the common carotid was available
for only 22 vessels, so that a ratio between the peak
frequency in the internal and common carotid arteries
could be calculated only for this number. Mean
frequency data were obtainable for only 20 carotid
arteries.

The Doppler ultrasound examination was performed
by a continuous wave directional Doppler ultrasound
device (Type 762 Kranzbiihler/Solingen — Germany)
with a 4 MHz transducer. The Doppler shift was repre-
sented on LED, storage oscilloscope and a strip chart
recorder as well. Calibration was performed with a 500
Hz impulse. The paper speed was set at 25 mm/sec.

Doppler frequency spectrum analysis was per-
formed simultaneously on a frequency analyzer (Type
8106 Kranzbiihler/Solingen — Germany). The fre-
quency range could be set to 0-2, 0-4, 0-8 and 0-16
kHz. The signals could be observed on a monitor with
16 grey scales. The signal duration was set to 1.25 or
2.5 sec respectively. With a cursor each area of interest

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of the frozen spectrum could be measured; the frequency was displayed in Hz.

The patient was examined in the supine position with the head rotated slightly away from the examiner. The handheld bidirectional Doppler probe was positioned over the common carotid artery and angled at about 45° to the skin surface and was adjusted until an optimal flow signal was elicited. The probe was then slowly moved along the course of the common carotid artery until the carotid bifurcation was reached, at which point there will be a slight change in the pitch of the Doppler signal.

The probe was then advanced along the course of the external carotid artery, which is characterized by its multiphasic Doppler signal and lower diastolic blood flow velocity. The signal of the external carotid artery may be manipulated by a vibration maneuver at the site of the superficial temporal or facial artery.

The Doppler probe was then repositioned over the carotid bifurcation angled slightly more dorsolateral to the external carotid artery until the internal carotid artery was insonated, recognized by its distinctive high flow velocity in both systole and diastole. The vibration test at the site of branches of the external carotid artery will be negative, when the internal carotid artery is insonated. When using a 4 MHz transducer, a systolic peak frequency exceeding 3500 Hz was considered to signify stenosis of the internal carotid artery.

The systolic mean frequency was read from the systolic peak of the strip chart recording and calculated in Hz with the aid of a 500 Hz calibration. The systolic peak frequency of the internal carotid artery was read from the systolic peak of the Doppler spectrum as well as the peak frequency of the common carotid artery. The peak frequency ratio (pfr) was calculated from the spectrum peak frequencies of the internal (fI) and common carotid (fC) artery: pfr = fI/fC. Johnston et al. proposed that percent stenosis of the internal carotid artery be calculated from the peak frequencies of the stenosed internal (fS) and normal common (fN) carotid artery: 100 × (1 − fN/fS).

Statistics

Statistical analysis was performed by a linear regression analysis of the measurements of two different days. A measurement of diagnostic value should be reproducible very well indicated by an adequate correlation of r ≥ 0.9 and a linear regression in the neighbourhood of the line of identical values (Y = X).

Though 16 of the 29 are paired vessels in 16 subjects, the data obtained from them were considered to be independent as changes in the severity of disease in contralateral vessels was not thought to have altered during the reproducibility study.

Results

All four normal carotid arteries were diagnosed by the noninvasive technique correctly as well as 24/25 stenosed internal carotid arteries.

The systolic peak frequency of the internal carotid artery could be reproduced very well (n = 29). The linear regression Y = 166 + 0.9X is very near the line of identical values. The coefficient of correlation r = 0.97 (p < 0.001) indicates very good correlation of both measurements (fig. 1).

The systolic mean frequency of the internal carotid artery — read from the strip chart recordings — was estimated in 20 blood vessels. This value can not be reproduced as demonstrated by the linear regression Y = 762 + 0.4X, which is far away from the line of identical measurements. Moreover, the coefficient of correlation r = 0.43 (p < 0.05) demonstrates very poor correlation of the two values (fig. 2).

The peak frequency ratio was evaluated twice in 22 carotid arteries. The linear regression Y = −0.58 + 1.24X is near the line of identical values. However, the coefficient of correlation r = 0.81 (p < 0.001) does not indicate as good correlation of the two measurements (fig. 3) as it could be demonstrated for the systolic peak frequency of the internal carotid artery.

The noninvasively calculated grade of stenosis can be reproduced as indicated by the linear regression Y = −0.74 + 1.0X (n = 22), which is near the line of identical measurements. The coefficient of correlation r = 0.87 (p < 0.001) does not show as sufficient correlation of the values (fig. 4) as it was shown for the systolic peak frequency of the internal carotid artery.

Discussion

A major innovation in noninvasive diagnosis of extracranial carotid artery disease was the introduction of direct Doppler sonography of the neck arteries. Interpretation of the Doppler frequency shift signal initially was performed by audible interpretation of the Doppler signals or examination of the mean frequency on a strip chart recording. Spectrum analysis of the Doppler shift frequency, however, might provide a method.
In our previous experience of 157 carotid arteries the Doppler spectrum analysis was normal in 45/47 angiographically proved normal carotid arteries, i.e. a specificity of 96 percent.11 16/17 totally occluded internal carotid arteries were diagnosed correctly. 7/14 stenoses with a reduction of the vessel diameter up to 25% were associated with an abnormal spectrum analysis. 78/79 stenoses exceeding 25% diameter reduction proved by angiography or by vascular surgery only were correctly predicted by real time Doppler spectrum analysis. Thus our previous data indicated a sensitivity in detecting carotid artery stenoses of approximately 91 percent.11

Our current study shows that these spectral peak frequencies obtained with the direct Doppler examination can be reproduced rather exactly. Other calculated spectral data such as the peak frequency ratio and the noninvasive estimate of stenosis are not as reproducible; moreover, their diagnostic accuracy does not exceed the systolic peak frequency of the internal carotid artery in our hands.10 The latter two parameters (ratio data) have similar correlation coefficients which is to be expected, as both values derive from the same measurements.

The factors affecting reproducibility may be classified as (a) hemodynamically-dependent, (b) anatomy-dependent and (c) examiner-dependent: (a) 1. There is no doubt that Doppler frequency spectral wave forms will be influenced by the central hemodynamics, e.g. stroke volume of the heart. This can be shown in patients with premature supraventricular or ventricular beats or in those with arrhythmia due to atrial fibrilla-

\[ 100 \times \left( 1 - \frac{f_N}{f_S} \right) \]
tion. However, none of our measurements has been influenced by arrhythmia. For practical reasons, we did not afford our patients an opportunity of habituation; the examinations were performed during clinical routine. Therefore measurements of heart rate and blood pressure were not done, deliberately. Hematocrit and blood viscosity were considered to be stable between the measurements. 2. Strong turbulent flow may obscure weak high frequency signals deriving from the residual lumen diameter. 3. While the measuring point is well defined for the internal carotid artery by its origin from the common carotid or by the stenotic lesion, the detection of flow signals of the proximal common carotid may vary for a distance of some centimeters. Moreover, the distal common carotid is not recommended for signal registration because of physiologically turbulent flow conditions. This is considered a potential source of error of the ratio data, e.g. the peak frequency ratio and the noninvasively calculated grade of stenoses. 4. The source of non-reproducibility of the systolic mean frequency is that the frequencies deriving from the zero-crossing detector do not represent real flow conditions in case of a stenosis. And the mean frequencies of the zero-crossing detector demonstrate some 20% differences from the real intensity weighted mean frequencies. It has been supposed, that a contralateral hemodynamic significant lesion may influence the ipsilateral Doppler-shift due to collateral blood flow, thus resulting in more increased systolic peak frequencies. Therefore, we omitted data on patients who underwent endarterectomy of the contralateral carotid artery before reproducibility could be tested. (b): The localisation of the Doppler probe to vessel anatomy is considered to be critical for several reasons: 1. The Doppler-shift depends on the angle between the vessel and the ultrasound beam. To keep the angle constant may be difficult, particularly when the examinations will be performed with handheld transducers. 2. A small deviation of the transducer may lead to zones of (poststenotic) turbulence, which affects the vector of flow relative to the transducer. 3. In some stenoses, especially those which are severe but are short in length, the zone of high systolic peak frequencies may be localized to a very short segment. This may result in difficulties to detect always the real representative signal of the stenosis. (c) Inadvertent compression of the carotid vessels caused by pressure on the transducer was carefully avoided, because this may lead to an accentuation of lumen narrowing with increasing peak frequencies.

However, our results concerning the systolic peak frequency of the internal carotid artery demonstrate that the transducer can be positioned to the internal carotid artery by acoustic control of the Doppler signals very exactly, thus resulting in only some hundred Hz difference from one day to the other. These data of reproducibility concerning Doppler spectrum analysis are very important, in particular because correlations of systolic peak frequencies and angiographic grade of stenosis have been reported. When performing follow up studies of carotid artery lesions — e.g. low grade stenosis in asymptomatic patients — you have to know the reproducibility of the measurements to decide whether an increase of the systolic peak frequency of the internal carotid artery means a progression of the vessel wall lesion.

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