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The Use of Preoperative Transcranial Doppler Variables to Predict Which Patients do Not Need a Shunt During Carotid Endarterectomy

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Objectives: *to analyse whether preoperative transcranial Doppler (TCD) variables can predict intraoperative shunt requirement.*
Design and methods: *the blood-flow velocity (BFV) in the major basal cerebral arteries was measured preoperatively with TCD, in 178 patients scheduled for CEA. Carotid artery compression and* CO_2 *reactivity tests were also performed. Intraoperative electroencephalography was used to decide whether a shunt was needed. Differences in the probability of shunt requirement between the categories of variables were assessed with crosstabs statistics.*
Results: *preoperative TCD criteria clearly identified a subgroup of 59 patients (33%) who did not require a shunt. In general, these patients appeared to have adequate collateral flow through the anterior communicating artery. In contrast, prediction of the need for a shunt was less reliable. TCD variables could predict the need for a shunt with a probability of only 60%.*
Conclusions: *preoperative TCD can be used to identify patients who do not require a shunt during carotid endarterectomy.*

Key Words: ICA obstruction; Carotid endarterectomy; Endovascular shunt; Transcranial Doppler; Common-carotid-artery compression test; CO_2 *reactivity.*

Introduction

There is no consensus about the necessity to use a shunt during carotid endarterectomy (CEA). The choice is between never using a shunt, always using a shunt, and selective shunting. An argument against using a shunt is the possibility of dislodging embolic material and thus increasing intraoperative complications;[1] however, not using a shunt may result in cerebral ischaemic complications in some patients. With selective shunting the decision of whether to use a shunt is based on the findings of intraoperative monitoring. Various monitoring techniques are used, such as measurement of stump pressure, cerebral blood flow (CBF), transcranial Doppler (TCD) flow velocity, EEG, or clinical monitoring during local anaesthesia.[1–6] The main goal of monitoring is to identify patients in whom cross-clamping would result in cerebral ischaemia. Shunting is performed in these patients to prevent ischaemic stroke. Selective shunting is reported to result in a lower overall complication rate.[1,7] Unfortunately, the criteria to determine the ischaemic threshold beyond which irreversible cerebral damage occurs are not exactly known, and the positive predictive value of the different methods used is often limited.[8] Of the methods used, the EEG potentially has the advantage of direct measurement of ischaemic changes developing in the effector organ.[5]

Various studies have focused on identifying preoperatively those patients who require shunting during CEA. Various methods have been investigated, such as the common-carotid-artery (CCA) compression test with monitoring of clinical symptoms or EEG changes, ocular plethysmography, and TCD with the cerebrovascular reactivity test or with CCA compression.[9] However, none of these preoperative tests could predict shunt requirement with a probability higher than about 50%.

The aim of the present study was to analyse preoperative haemodynamic variables, as measured with TCD, with respect to intraoperative shunt requirement. Besides baseline TCD investigation of the major basal cerebral arteries, we also tested the effect of CCA compression on the side scheduled for CEA and the

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effect of CO_2 inhalation bilaterally. We did not primarily focus on the identification of patients requiring a shunt, but rather those who do not require a shunt. The practical consequence of reliable identification of such a subgroup is that intraoperative monitoring of these patients would be redundant. In the present study we used ischaemic EEG changes as the criterion for whether a shunt was needed or not.

Patients and Methods

Patients

One hundred and seventy-eight consecutive patients with stenosis of the internal carotid artery (ICA) of at least 70%, who were scheduled for CEA during the period September 1994 to September 1996, were included in the study. The severity of ICA stenosis was determined by angiography (70% stenosis according to North American Symptomatic Carotid Endarterectomy Trial criteria). The hemisphere of the carotid artery scheduled for CEA was called the CEA side and the other hemisphere was called the contralateral side. The mean age of the patients was 66 ± 9 years and 71% were male ($n = 127$). In addition to stenosis of the ICA on the CEA side, 21% of the patients had an occlusion of the contralateral ICA ($n = 37$), 22% a contralateral stenosis of at least 70% ($n = 39$), and 19% a contralateral stenosis of less than 70% ($n = 33$).

In the year prior to inclusion 143 patients (80.5%) had symptoms. In 112 patients (63%) symptoms were restricted to the CEA-side hemisphere. Of these patients, 24 had a minor stroke, 61 had one or more transient ischaemic attacks, and 27 experienced ocular symptoms (i.e. transient monocular blindness or impaired vision due to chronic retinal ischaemia). In 19 patients (10.5%) signs and symptoms were restricted to the contralateral side (four with a minor stroke, 13 with transient ischaemic attacks and two with ocular symptoms). Twelve patients (7%) had symptoms on both sides. Thirty-five patients (19.5%) were asymptomatic.

The Ethics Committee of the University Hospital Utrecht approved the study and all patients gave their informed consent.

TCD examination

The TCD examination was generally performed 2 days (median = 2; P5/P95 range 1–35 days) before CEA with a DWL Multidop-X device (Sipplingen, Germany) using a 2-MHz pulsed Doppler probe. The blood-flow velocity (BFV) was determined bilaterally in the M1 segment of the middle cerebral artery (MCA), the A1 segment of the anterior cerebral artery (ACA), the P1 segment of the posterior cerebral artery (PCA), the ophthalmic artery (OA), and the basilar artery (BA). The direction of blood flow in the ACA and the OA was also noted. The BFV was documented as the mean peak-flow velocity measured over a 5-second period.

During CCA compression tests, the BFV was continuously measured with the TCD probes fitted in a light metal frame, which was firmly fixed to the head with two earpieces and an adjustable nose-saddle (manufactured by DWL). Patients were lying down with their eyes closed. First, the BFV in both ACAs was simultaneously measured and CCA compression on the CEA side was performed for 5 s. Then, the TCD probes were adjusted to measure the BFV in both MCAs and the CCA compression was repeated. The measured changes in BFV are expressed relative to the baseline BFV (before compression) and the flow direction in the ACAs before and during compression was assessed.

The CO_2 reactivity was measured simultaneously in both MCAs. After a 2-min baseline period, patients inhaled carbogene (5% CO_2 and 95% oxygen) for another 2 min. A 5-second spectral TCD recording was made during the baseline period and after 1.5 min of carbogene inhalation. At the same moments blood pressure (BP) was measured with an automatic device (Omega 1000; Invivo Research Laboratories Inc.). The CO_2 content of the inspired gas was continuously monitored with an infrared gas analyser (Mijnhardt). The CO_2 reactivity after 1.5 min of inhalation of carbogene was determined as the change in BFV relative to the baseline BFV.

There were no complications during the CCA compression or CO_2-reactivity tests.

Anaesthetic regimen and EEG monitoring during CEA

Anaesthesia was standardised to reduce the variance in EEG data among patients. Patients were orally premedicated with benzodiazepines prior to arrival in the operating room. Anaesthesia was induced with etomidate and fentanyl and maintained with N_2O in oxygen and propofol. Local cervical plexus block ensured that a relatively low level of general anaesthesia was needed, enabling an optimal assessment of EEG changes indicative of cerebral ischaemia. Pancuronium was used for neuromuscular relaxation.

Steady-state end-tidal CO_2 was kept between 4.8 and 5.4 kPa. Nasopharyngeal temperature was maintained between 35.5 and 37.0 °C.

The EEG was recorded with silver–silver chloride electrodes attached to the skin with collodion at electrode positions according to the international 10–20 system. A 16-channel montage ($Fp_{1/2}$, $F_{7/8}$, $T_{3/4}$, $T_{5/6}$, $O_{1/2}$, $F_{3/4}$, $C_{3/4}$, and $P_{3/4}$) with Cz as common reference was used. The EEG was recorded continuously on paper with a 21-channel Elema-Siemens encephalograph, bandpass 0.13–70 Hz (−3 dB) and sensitivity 70 or 100 μV/cm. The paper speed was 1.5 cm/s. EEG recordings were visually assessed by an experienced clinical neurophysiologist in the operating room (GHV or ACvH). Any visual diminution or loss of alpha and beta activity, with or without a concomitant increase in theta or delta activity, was considered indicative of cerebral ischaemia. We did not rely on quantification of a minimal required magnitude of EEG changes due to the subjective character of the assessment during on-line intraoperative monitoring (an additional – retrospective – analysis was performed to determine the interobserver agreement between GHV and ACvH with respect to the EEG assessment for shunt decision; kappa was 0.84). If these EEG changes occurred during the first 2 min of cross-clamping of the internal and external carotid artery, selective shunting was performed. These patients are referred to as the shunt group ($n=29$; 16% of the studied group). The other patients, in whom no ischaemic EEG changes occurred, are called the no-shunt group ($n=149$).

Eight strokes occurred during or after the operation (4.5%). In the shunt group, one mild and one fatal intraoperative stroke occurred and one fatal stroke occurred during the first postoperative week. This last stroke was located in the contralateral hemisphere, although the ICA on that side was not stenosed. All other infarcts were located in the CEA-side hemisphere. In the no-shunt group, one severe intraoperative stroke occurred, and one fatal and three severe strokes occurred in the first postoperative week. The EEG of the no-shunt patient with the intraoperative stroke was reassessed after the operation and again no signs of ischaemia could be detected. The CT scan of this patient showed a frontal infarction. There was no statistically significant difference in the number of complications between the shunt and no-shunt groups.

Statistical analysis

Twenty variables were derived from the preoperative measurements. If BFV could not be determined in an intracranial vessel, this was treated as a missing value and was not included in the statistical analysis. The continuous variables were classified in categories, based on the distribution and characteristics of the data and on clinical arguments.

Differences in the probability of shunt requirement between the categories were assessed in crosstabs and were analysed with the Pearson's Chi-squared test or the Fisher's exact test available in the SPSS statistical software (version 6.1.3). If a variable with more than two categories did not fulfil the criteria for the crosstabs analysis, categories were combined in order to demonstrate statistically significant differences in shunt requirement. To correct for the number of statistical tests performed, an overall significance level of $p<0.01$ was chosen.

Results

The variables and categories used in the analysis are shown in Table 1. The results of the crosstabs analysis of variables that showed statistically significant differences between categories are presented in Table 2 (significance level $p<0.01$). For this analysis, differences were analysed between the no-shunt group and the total shunt group.

There were several categories that were never associated with the need for a shunt: a reversed blood flow in the CEA-side ACA, a maximal 10% decrease in the BFV in the CEA-side MCA during CCA compression, minor changes or a flow-reversal in the CEA-side ACA or a >50% increase in the BFV on the contralateral ACA (Table 2). Fifty-nine patients were identified where at least one of these variable categories was present. Thus, a subgroup consisting of 33% of the studied patients could be identified, which did not require a shunt.

In contrast, as was expected based on previous literature, we found no variable categories that were indicative of definite shunt requirement, but several categories were associated with an increased shunt probability (see Table 2). Selection of patients on the basis of the presence of at least one variable category that was associated with a shunt probability of ≥50% resulted in a group of 27 patients; the shunt probability was 52%. If a shunt probability of ≥40% was used as criterion, we could identify 47 patients with a shunt probability of 36%. Sixty-nine patients had at least one variable category that was associated with ≥30% shunt probability, resulting in an overall probability of 29%. The lower overall shunt probability was because of our selection process, by which patients with a missing

Table 1. Variables and categories used in the analysis.

Variable	Categories (number and definition)	
General		
Age	3	≤45; 45–65; >65 years
Gender	2	male; female
Clinical symptoms CEA side	3	asymptomatic; ocular; cerebral
Clinical symptoms contralateral side	3	asymptomatic; ocular; cerebral
ICA occlusion contralateral side	2	no; yes
Standard TCD		
MCA CEA side	2	≤35; >35 cm/s
MCA contralateral side	3	≤35; 35–55; >55 cm/s
ACA CEA side	4	≤0; 0–50; 50–70; >70 cm/s
ACA contralateral side	4	≤0; 0–30; 30–70; >70 cm/s
OA CEA side	3	≤ −25; −25–0; >0 cm/s
OA contralateral side	3	≤ −25; −25–0; >0 cm/s
PCA CEA side	2	≤45; >45 cm/s
PCA contralateral side	4	≤25; 25–45; 45–65; >65 cm/s
BA	3	≤45; 45–65; >65 cm/s
CCA compression test at CEA side		
MCA CEA side	4	≤ −70%; −70 to −40%; −40 to −10%; > −10%
MCA contralateral side	3	≤ −30%; −30 to −10%; > −10%
ACA CEA side	4	−25–25% (minor changes); ≤ −25% (normal→normal); normal→reversed; >25% (reversed→reversed)*
ACA contralateral side	3	≤50%; >50%; reversed*
CO_2 reactivity test		
CEA side	3	≤10%; 10–30%; >30%
Contralateral side	3	≤10%; 10–30%; >30%

A range given as for example 10–30 means excluding 10 and including 30. The flow velocity in an ACA or OA with a reversed flow is given as a negative value.

* "Normal" and "reversed" refer to the direction of blood flow; the arrow indicates the change in blood flow direction during CCA compression.

value for a single variable were added to the no-shunt group. The PCA categories with an increased BFV, which is indicative of collateral blood flow through the posterior communicating artery (PCoA) on the same side, were associated with the same shunt probability as the other PCA categories.

Discussion

Our results showed that a subgroup of patients could be distinguished, based on preoperative TCD variables, in whom the lack of need for a shunt could be predicted with a very high probability. In general, patients in this subgroup were characterised by a reversed flow in the CEA-side ACA, which suggests that there is collateral blood flow through the anterior communicating artery (ACoA) towards the CEA-side MCA. During CCA compression on the CEA side, there were no relevant changes in BFV in the MCA on the CEA side (maximally 10% decrease in BFV) and BFV in the contralateral ACA increased by >50%. BFV in the ACA on the CEA side showed minor changes during CCA compression (maximally 25% change) and in some patients the blood flow reversed. During intraoperative cross-clamping these patients can be expected to have adequate ACoA collateral flow towards the CEA side. The PCoA collateral circulation did not appear to play a role.

Concerning shunt prediction, we could only identify patients with a higher-than-average shunt probability. With the studied TCD variables, we could only predict a 60% probability of shunt requirement. A shunt is more likely to be needed when the contralateral ICA is occluded and there is collateral blood flow through the ACoA from the CEA side towards the contralateral side (CEA-side ACA BFV >70 cm/s and contralateral ACA BFV reversed flow). In these patients collateral compensatory flow was expected to be inadequate because there was also a decreased BFV in the contralateral MCA (≤35 cm/s) and a decreased contralateral CO_2 reactivity (≤10%). Reversed flow in the contralateral OA is indicative of a decreased perfusion pressure at the distal end of the ICA on this side. During CCA compression on the CEA side, the BFV in the CEA-side MCA decreased by more than 70% and in the contralateral MCA by more than 30%. As in the no-shunt patients, in shunt patients PCoA collateral

Table 2. Results of the crosstabs analysis. The total number of patients in each category is given ($n=$) and the shunt probability within this category (shunt%). Differences in shunt probability between the categories of a variable were tested (significance level $p<0.01$). Crosstabs analysis of variables found in Table 1 but not listed in Table 2 was also performed; none of these variables revealed statistically significant differences in shunt probability between the categories.

Variables and categories	$n=$	Shunt%	Used test and p-value
General			
Clinical symptoms contralateral side			
asymptomatic	147	12%	Fisher's exact test
ocular	8	13%	(asympt. or ocular vs. cerebral)
cerebral	23	44%	$p<0.001$
ICA occlusion contralateral side			
no	140	11%	Fisher's exact test
yes	37	35%	$p<0.005$
Standard TCD			
MCA contralateral side (cm/s)			
≤ 35	12	33%	crosstabs
35 through 55	63	10%	$\chi^2=5.1$
>55	96	19%	$p=$NS
ACA CEA side (cm/s)			
≤ 0	23	0%	crosstabs
0 through 50	49	10%	$\chi^2=15.5$
50 through 70	34	24%	$p<0.005$
>70	26	39%	
ACA contralateral side (cm/s)			
≤ 0	19	37%	crosstabs
0 through 30	6	17%	$\chi^2=10.4$
30 through 70	62	13%	$p=$NS
>70	55	7%	
OA contralateral side (cm/s)			
≤ -25	20	35%	crosstabs
-25 through 0	23	26%	$\chi^2=10.0$
>0	123	11%	$p<0.01$
CCA compression test (at CEA side)			
MCA CEA side (% change)			
$\leq -70\%$	13	62%	crosstabs
-70% through -40%	57	23%	$\chi^2=27.3$
-40% through -10%	42	7%	$p<0.001$
$>-10\%$	26	0%	
MCA contralateral side (% change)			
$\leq -30\%$	14	64%	crosstabs
-30% through -10%	31	16%	$\chi^2=27.3$
-10%	90	9%	$p<0.001$
ACA CEA side*			
$\leq -25\%$ (normal flow direction)	38	26%	Fisher's exact test
-25% through 25% (minor changes)	14	0%	($<-25\%$ vs. the other categories)
>25% (reversed flow direction)	10	0%	$p<0.001$
normal to reversed flow direction	13	0%	
ACA contralateral side			
reversed flow present	8	50%	crosstabs
$\leq 50\%$	60	10%	$\chi^2=12.9$
>50%	14	0%	$p<0.005$
CO_2-reactivity test (% change)			
contralateral side			
$\leq 10\%$	13	46%	crosstabs
10% through 30%	32	19%	$\chi^2=10.3$
>30%	103	12%	$p<0.01$

A range given as for example 10 through 30 means excluding 10 and including 30. The flow velocity in an ACA or OA with a reversed flow is given as a negative value.

* "Normal" and "reversed" refer to the direction of blood flow; the arrow indicates the change in blood flow direction during CCA compression.

blood flow did not appear to play a major role in shunt prediction. In conclusion, this subgroup of shunt patients had compromised contralateral haemodynamics, which can explain the higher incidence of cerebral symptoms (44%). It is unlikely that during intraoperative cross-clamping on the CEA side adequate ACoA collateral compensation towards the CEA side occurs. Thus, a shunt will be required. TCD variables appeared to be better shunt predictors, especially if combined with the CCA compression test, than the existence of a contralateral ICA occlusion alone (35% shunt requirement).

Our results confirm the findings of Kearse *et al.*, who found no association between age or preoperative symptoms on the CEA-side hemisphere and the development of intraoperative ischaemic EEG patterns during carotid artery cross-clamping.[3] In this study, the association between symptoms of the contralateral hemisphere was not investigated. In another study, the same investigators studied angiographic collateral patterns in relation to shunt requirement.[10] An ACoA collateral pattern with flow reversal on the CEA-side A1 segment was associated with shunt requirement in 21% of patients, compared with 50% in patients without this pattern. They found this angiographic collateral pattern in 43 of 67 patients, which is a far higher proportion than we found with TCD in our population (in 23 of 178 patients). In our study, patients showing the above-mentioned collateral pattern never needed a shunt. In their study, Lopez-Bresnahan *et al.*[10] reported an overall shunt requirement of about 30%, compared with our 16% shunt requirement. It is impossible to give a good explanation for these incongruous findings. The discrepancy might, for instance, be due to differences in the studied populations or differences in the methods of anaesthesia, surgery, and/or monitoring. Their finding that angiographic collateral patterns through the PCoA or CEA-side OA did not protect against intraoperative ischaemic EEG changes is in accordance with our results. The same holds for the finding that a contralateral ICA occlusion or a reversed flow in the contralateral OA was more frequently associated with shunt requirement. Our results are consistent with the final conclusion of Lopez-Bresnahan *et al.*[10] that particularly the collateral flow through the ACoA decreases the risk of intraoperative cerebral ischaemia. Other investigators also found a higher shunt requirement when there is contralateral ICA occlusion.[4,11]

In a study by Schneider *et al.*,[2] patients lacking ACoA or PCoA collateral blood flow also had an increased risk of intraoperative cerebral ischaemia. However, the TCD criteria they used to determine the presence of a PCoA or ACoA are unclear, and patients with either of these collateral circulations were treated as one subgroup. Therefore, it is not possible to determine the role of the PCoA in the prevention of cerebral ischaemia from their results. Chiesa *et al.* used preoperative TCD BFV changes during CCA compression tests to predict major EEG changes during intraoperative cross-clamping in three out of four patients, but they could not predict moderate EEG changes.[12] This supports our finding that TCD with CCA compression enables the identification of a subgroup with an increased shunt probability, but not the definite need for a shunt.

Thiel *et al.* found no correlation between an impaired CO_2-reactivity on the CEA side and intraoperative ischaemic changes during cross-clamping.[13] Unfortunately, they did not report the results for the contralateral CO_2-reactivity. An impaired preoperative CO_2-reactivity reflects compromised haemodynamics and is suggestive of high-grade ICA stenosis on the ipsilateral side and already a very limited blood flow through this artery. Further obstruction of the ICA, as with cross-clamping, might not further affect the blood flow towards this hemisphere. However, with less severe ICA stenosis, the blood flow through the ICA changes considerably during cross-clamping and the haemodynamic consequences are largely dependent on the potential of the collateral flow. The contralateral blood flow is then of great importance for preventing cerebral ischaemia on the CEA-side hemisphere. Our results confirm this concept, since an impaired contralateral CO_2-reactivity was associated with more frequent shunt requirement. However, the CO_2-reactivity test did not contribute to shunt prediction when used in combination with the standard TCD investigation and carotid artery compression tests.

In conclusion, we could predict about one-third of our patients who did not require a shunt, which could form the basis for selective monitoring. However, it was more difficult to predict which patients do require a shunt.

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