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ORIGINAL COMMUNICATION

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Differences in number, size and location of intracranial microembolic lesions after surgical versus endovascular treatment without protection device of carotid artery stenosis

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Abstract *Background and purpose* The benefit of carotid endarterectomy in symptomatic high-grade stenosis has long been proven. The role of angioplasty as an alternative is still a matter of debate. We compared the occurrence of intraprocedural microembolic signals and ischemic lesions between carotid endarterectomy (CEA) and carotid angioplasty with stent placement (CAS) without a protection device. *Methods* 88 patients who underwent a CEA and 41 patients who underwent CAS were prospectively investigated. One day before and after the intervention diffusion weighted MRI-studies were obtained. In 21 CEA and 18 CAS patients transcranial Doppler (TCD) monitoring was performed during the procedure to detect microembolic signals (MES). *Results* DWI-lesions could be detected after intervention in 17% of the CEA patients compared with 54% of the CAS patients ($p < 0.005$). The median lesion volume was 0.08 cm^3 in the CEA group and 0.02 cm^3 in the CAS group ($p < 0.001$). Ischemic complications consisted of 2 strokes (2.3%) with symptoms lasting more than seven days in the CEA group and 1 stroke (2.4%) in the CAS group. The median number of MES in the CEA group was 17 versus 61 in the CAS group ($p < 0.001$). No significant correlation was found between the total number of MES and ischemic lesions in either group. *Conclusion* A larger number of emboligenic particles with smaller volume is detached during CAS. Additionally DWI lesions were observed in different territories after CAS but not after CEA. Conventional TCD emboli detection is not useful to compare interventional therapies of the carotid arteries.

Key words angioplasty · balloon · endarterectomy · carotid · diffusion magnetic resonance imaging · intracranial embolism · ultrasonography · doppler · transcranial

Introduction

Large clinical trials have demonstrated the benefit of carotid endarterectomy (CEA) for patients with symptomatic high-grade stenosis of the internal carotid artery (ICA) [1, 3, 17]. Increasingly, carotid angioplasty and stent placement (CAS) is being offered worldwide as an alternative. Shorter hospital-stays, avoidance of anesthesia and avoidance of surgical incision with its risk of iatrogenic cranial nerve palsy makes CAS attractive. Since the first intervention in a 32 year old woman treated for fibromuscular dysplasia in 1979 and the first use of a stent in 1989 this method has been continuously improved [13]. However, reliable outcome data comparable to those for CEA have not been available until re-

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cently. The first and only published large prospective multicenter study that compared results of angioplasty and surgery was CAVATAS [2], which documented a high but almost equal number of traceable clinical complications due to cerebral ischemia in both groups (10 % frequency of death or any stroke in both groups). The only parameter of comparison in this study was the clinical outcome.

Diffusion weighted MRI (DWI) offers the possibility of making even small and therefore asymptomatic lesions visible shortly after their emergence [12]. Online detection of intracranial microembolic signals (MES) at the time of their occurrence using TCD offers the unique opportunity to analyse emboli arising during CEA/CAS quantitatively and to assign them to predetermined phases of the intervention. The value of the detected signals for analysing the associated risk of cerebral ischemia has been interpreted controversially [4–8, 18]. By using DWI and TCD emboli detection we compared the risk of distal embolisation between both therapeutic modalities. Furthermore, the clinical validity of sonographically detectable MES was examined by comparison with the DWI-findings.

Patients and methods

Patients

We prospectively examined 88 patients (31 female, median age 68 years) who underwent a CEA and 41 patients (14 female, median age 71 years) who underwent a CAS. The severity of the carotid stenosis was evaluated by measuring the peak systolic velocity (PSV) with angle correction at the narrowest point of the stenosis [9]. The degree of stenosis was classified as mild (< 200 cm/s), moderate (200–299 cm/s) and severe stenosis (≥ 300 cm/s or decrease of PSV combined with distinct duplexsonographic signs of filiform stenosis) (Table 1). In all cases the stenosis was caused by arteriosclerosis. 42 (48 %) CEA patients and 18 (44 %) CAS patients had been symptomatic within six months prior to intervention.

The primary criteria for performing CEA or CAS was the patient's and treating physician's preference. Morphological criteria as determined by ultrasonographic examination were not taken into consideration for this decision. The only angiographic feature that was considered prohibitive for CAS was stenosis caused by kinking. All patients gave written informed consent. The methods used in the study were approved by the local ethics committee.

Study design

All patients were examined one day before and one day after the intervention by a neurologist who did not have any information regarding the MRI-findings. DWI was performed on the day before as well as the day after the intervention. MES monitoring was performed on the day before, during the entire procedure and on the day after the procedure.

MRI

MRI-studies were performed on a 1.5 T whole body imaging system with a head coil (Magnetom Symphony Quantum gradient, Siemens Medical Systems, Germany). Whole brain DWI was carried out with an isotropic echo planar sequence. Sagittal, coronal and transversal studies were obtained, each of them with b values of 0, 500 and 1000 s/mm^2, TR 4006 ms, TE 83 ms, quantum gradient 30 mT/m, slew rate 125 mT/m/ms, rising time 240 µs, slice thickness 4–6 mm, gap 1.5 mm, 128 x 128 matrix and 220 x 220 mm field of view. For minimising the effects of diffusion anisotropy, the diffusion-weighted data were automatically processed by the scanner's software (Numaris© 3.5). ADC maps were also automatically processed by the scanner's software.

The MRI was conducted with special consideration of number and location of lesions. All images were re-analysed by two experi-

Table 1 Baseline characteristics of patients, *NS* not significant

	CEA				CAS				P (total)
	DWI lesions	No DWI lesions	P	Total	DWI lesions	No DWI lesions	P	Total	
N	15	73		88	22	19		41	< 0. 001
Female	3 (20%)	28 (38%)	NS	31 (35%)	8 (36%)	6 (32%)	NS	14 (34%)	NS
Age (median [range], years)	70 [53, 83]	68 [46, 90]	NS	68 [46, 90]	74 [55, 80]	67 [51, 83]	NS	71 [51, 83]	NS
Ipsilateral carotid stenosis:									
mild	0 (0%)	3 (4%)	NS	3 (3%)	0 (0%)	0 (0%)	NS	0 (0%)	NS
moderate	9 (60%)	28 (38%)	NS	37 (42%)	7 (32%)	8 (42%)	NS	15 (37%)	NS
severe	6 (40%)	42 (58%)	NS	48 (55%)	15 (68%)	11 (58%)	NS	26 (63%)	NS
Symptomatic	10 (67%)	32 (44%)	NS	42 (48%)	13 (59%)	5 (26%)	NS (0.06)	18 (44%)	NS
Peripheral vascular disease	1 (7%)	13 (18%)	NS	14 (16%)	4 (18%)	3 (16%)	NS	7 (17%)	NS
Ischemic heart disease	6 (40%)	18 (25%)	NS	24 (27%)	11 (50%)	10 (53%)	NS	21 (51%)	< 0.05
Hypertension	14 (93%)	59 (81%)	NS	73 (83%)	22 (100%)	17 (89%)	NS	39 (95%)	NS
Smoker	4 (27%)	28 (38%)	NS	32 (36%)	8 (36%)	9 (47%)	NS	17 (41%)	NS
Increased cholesterol	11 (73%)	31 (42%)	< 0.05	42 (48%)	20 (91%)	13 (68%)	NS	33 (80%)	< 0.001
Diabetes	9 (60%)	20 (27%)	< 0.05	29 (33%)	11 (50%)	2 (11%)	< 0.01	13 (32%)	NS
Atrial fibrillation	1 (7%)	3 (4%)	NS	4 (5%)	1 (5%)	1 (5%)	NS	2 (5%)	NS

enced neuroradiologists who were blinded to clinical details including the kind of intervention. An acute ischemic lesion in DWI was only diagnosed if an increased signal intensity was visible at least on two planes, if a corresponding decreased signal intensity was detected in the apparent diffusion coefficient (ADC) image, if the lesion was not seen in the preprocedural films and if both neuroradiologists agreed on their DWI findings. Volume size was obtained by manually tracing the lesions with the internal measuring function of the magnetic resonance imaging scanner and multiplying the area by slice thickness. These volumes were added up plane by plane to get the entire volume of one lesion. Many lesions, however, were smaller than the selected slice thickness, therefore one of the other planes was also used to determine the precise lesion dimension.

TCD

For microembolic monitoring we used a 2 MHz pulse-wave transcranial Doppler device (DWL Elektronische Systeme MULTI-DOP T2, Sipplingen, Germany) for simultaneous long-term insonation of both middle cerebral arteries using simultaneous 64-point fast-Fourier transformation and bigate-technique. The above mentioned parameters were chosen according to the recommendations of the International Consensus Group on Microembolus Detection [16]. We chose an emboli detection level of 11 dB. TCD recording quality was continuously observed by one investigator. Monitoring took place during the whole procedure and for another 15 minutes after pulling out the last catheter or wound closure respectively. During CAS a second investigator observed the intervention and documented all potential sources of artefacts, including the applied contrast medium. All MES were saved automatically and analysed offline. The following five phases were distinguished during CEA: before and during the first cessation of blood flow, after the first cessation of blood flow (shunt period) as well as during and after the second cessation of blood flow. During CAS the following phases were distinguished: overview- and selective angiography, positioning of the guidewire, the angioplasty catheter, the stent catheter and subsequent angioplasty catheter(s). As is already well known, during the passage of contrast medium a wide and high increase of signal intensity can be observed [15]; therefore signals that occurred during this phase of the procedure were not counted.

Intervention

CEA: All patients underwent a classical CEA by an experienced surgeon with intraoperative insertion of a shunt.

The procedure was performed under normotensive, normocapnic general anesthesia. As a standard procedure a thrombendarterectomy with obligate shunting was performed using a size-compatible BARD-Shunt (IMPRA, Inc. Tempe™, USA). Arteriotomy was routinely closed with a pre-clotted Dacron patch (Hema Carotid Patch Knitted And Knitted Ultrathin, Intervascular, La Ciotat Cedex™, France). Average clamping time was 2’39 minutes for the first and 2’54 minutes for the second clamping. The patients were anticoagulated with 5000 I.E IV heparin at the beginning of the operation that was antagonised completely by protamine afterwards.

CAS: All CAS were performed by a team of an experienced angiologist and an experienced interventional radiologist. In all cases angiography and angioplasty took place in one session. No protection devices were used. The stenosis was predilated before stent placement.

All patients received a daily dose of 200 mg acetylsalicylic acid (ASA) at least one day before intervention and a loading-dose of 600 mg clopidogrel the day before intervention. At the beginning of the intervention 130 I. E. heparin per kg of body weight were given. After the intervention clopidogrel was continued with a dose of 75 mg per day for four weeks and 200 mg ASA per day not time-limited.

After placement of a short 7-french-sheath (Radiofocus Introducer II, Terumo™) a guiding wire (J-wire, 0.035’, 180 cm, Terumo™) was introduced into the aortic arch and used to place a pigtail-catheter (F-5, 100 cm, Royal Flush Plus PIG, William Cook Europe™) for an angiographic overview demonstration. A selective angiographic demonstration of the affected vessel was then usually carried out using a Headhunter catheter (F 5, 100 cm, Hinck Headhunter cerebral, Torcon NB advantage H1, William Cook Europe™). The guiding wire was exchanged with a 0.020’ gold wire (Schneider, Boston scientific™) and the dilatation element of an angioplasty catheter (mostly F-5, Smash, 4 mm, Boston Scientific™) with defined maximum diameter was passed over the wire and placed within the stenosis. It was manually inflated for approximately five seconds. Thereafter a self-expanding stent (Carotid Wallstent OTW, Boston Scientific™) was placed covering the stenosis and the adjacent arterial segments and released under X-ray control. In all cases balloon dilation after placement of the stent was performed to relieve any residual stenosis. After performing a final angiogram to assess the result, the catheter was removed. The sheath was left in place until the partial thromboplastin time had fallen to less than 60 seconds.

Statistics

Statistical analysis was performed in cooperation with the Institute of Medical Statistics and Epidemiology of the Technical University of Munich. The age distribution, lesion volume and number of MES were specified as median and range. For analysis concerning these parameters the Wilcoxon rank-sum test was used. The Pearson product-moment correlation coefficient was used to measure the relationship between MES and DWI-lesions. All other analysis was performed by Fishers Exact Test for 2-by-2-contingency tables. A p-value < 0.05 was considered statistically significant. All analyses were done with JMP© 5.0.1a (SAS Institute, USA).

Results

DWI

In 15 (17 %) of 88 CEA patients DWI-lesions could be detected after intervention compared with 22 (54 %) of 41 CAS-patients ($p < 0.001$, Table 2). The median lesion volume was 0.08 cm^3 in the CEA group and 0.02 cm^3 in the CAS group ($p < 0.001$, Table 2).

All lesions seen after CEA were located in the territory of the target vessel. Four patients (9.8 %) who underwent CAS developed DWI-lesions not only in the territory of the target vessel but also in territories that were supplied by the contralateral ICA or the vertebral arteries. In two cases DWI-changes were found in the cerebellum. In one case a hyperintense signal was seen in the contralateral anterior cerebral artery territory without any angiographic hint of a supply of this area by the other ICA. One patient showed additional DWI lesions in the cerebellum and the contralateral middle cerebral artery territory. In all four cases the right ICA was dilated. The total number of lesions found was not related to the side of the treated artery.

We observed no significant differences in patient demographic data, characteristics of the stenosis, or vascular risk factors between the group with positive and negative DWI findings except for prevalence of diabetes

Table 2 DWI lesions, adverse outcomes and MES in CEA- and CAS-patients

	CEA	CAS	P
DWI			
DWI lesions	15 (17%)	22 (54%)	< 0.001
lesion volume (mm^3)			
mean	0.39	0.03	< 0.005
median [range]	0.080 [0.012, 6.000]	0.020 [0.001, 0.524]	< 0.001
Adverse outcomes			
Intracranial hemorrhage	0	0	NS
Stroke (symptoms > 7 days)	2 (2.3%)	1 (2.4%)	NS
Cranial nerve palsy	7 (8%)	0 (0%)	NS
TCD (n)	21	18	
MES (median [range])	17 [2, 59]	61 [7, 176]	< 0.001

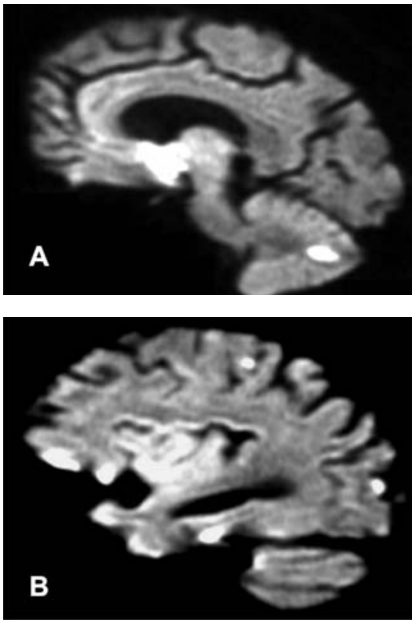

Fig. 1 **A, B:** 67-year-old female patient after CAS of the right ICA, lesions in the MCA territory ipsilateral and in the cerebellum

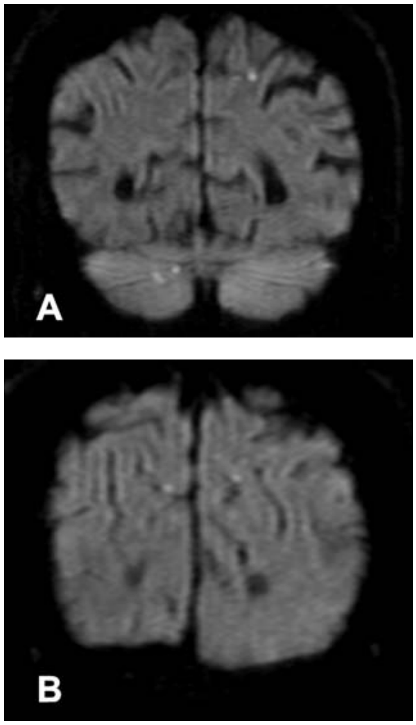

Fig. 2 **A, B:** 75-year-old male patient after CAS of the right ICA, lesions in the territory of the MCA bilateral and in the cerebellum

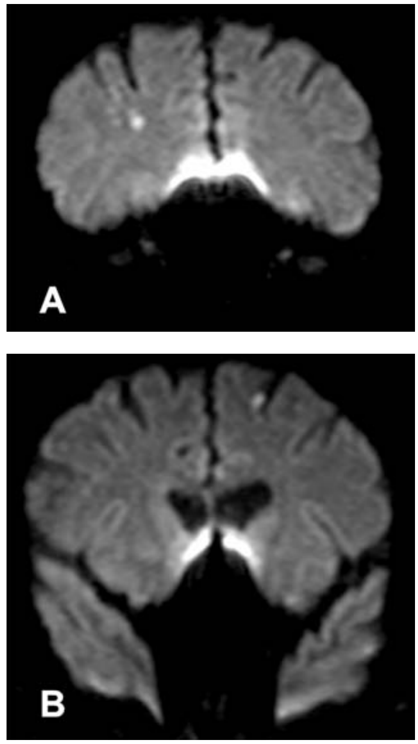

Fig. 3 **A, B:** 65-year-old male patient after CAS of the right ICA, high DWI signals in the ipsilateral MCA and contralateral ACA

and increased cholesterol. Diabetes was positively associated with the occurrence of DWI lesions in both groups, whereas a significant association between an increased cholesterol blood level and the occurrence of DWI lesions was found only in the CEA group (Table 1).

TCD

TCD was not obtained at the beginning of the study because this technique was not available in our centre at the time the study was initiated. Later 21 CEA patients and 18 CAS patients were successfully monitored by TCD.

The median number of MES in the CEA group was 17, ranging from 2 to 59. No significant correlation could be found between the number of MES and the number of ischemic lesions ($p = 0.4$). The median number of MES in the CAS group was 61, ranging from 7 to 176. No positive correlation could be found between the number of MES and the number of ischemic lesions ($p = 0.3$). The difference between the mean number of MES in both groups was significant ($p < 0.001$).

Neurological outcome

Ischemic complications consisted of two strokes (2.3 %) in the CEA group and one stroke (2.4 %) in the CAS group, all occurring within 24 hours after the intervention. No patient in either group showed neurological deficits without corresponding DWI lesions.

One CEA patient developed a mild paresis of his right hand, another a Broca's aphasia. Three patients underwent reoperation because of postoperative bleeding. Seven CEA patients developed cranial nerve palsies (mild hypoglossal nerve palsy (n = 5), recurrent laryngeal nerve palsy (n = 1), a further patient developed a peripheral facial palsy ipsilateral to the stenosis, probably as a consequence of a pressure lesion). One CAS patient developed a mild paresis of the right upper and, to a lesser extent, the right lower extremity. None of the CAS patients developed cranial nerve palsy.

Discussion

The main aim of our investigation was to compare the occurrence of DWI lesions between the invasive methods. We observed significantly more post-interventional DWI-lesions in the CAS group, indicating that during CAS a much larger number of embolic particles is detached than with CEA. However, the embolic particles during CAS result in smaller lesions, as demonstrated by the significantly smaller mean volume of the DWI-lesions. In contrast to our study with DWI lesions in 54 % after stent implantation, Jaeger et al. observed ipsilateral DWI lesions in only 29 % of 67 patients [10]. The difference from our findings may be caused by a different technique of stenting or sensitivity of the MRI-studies. Differences consist in a stronger gradient field strength and a faster rising time in our study enabling shorter echo times (TE 103 versus 83 ms) and the application of two acquisitions instead of one, both improving resolution and sensitivity of lesion detection. Furthermore we performed DWI in axial, coronal and sagittal planes instead of only the axial view. Since many of the lesions were small, they could be detected only in two instead of three planes.

Müller et al. found DWI lesions after CEA in 34 % of 77 procedures [14]. These data were not comparable with ours because of a 4 times higher incidence of stroke and a different CEA technique; in the majority of procedures no shunt was used.

To investigate the origin and mechanism of emboli detachment we performed TCD monitoring while simultaneously and precisely documenting all steps of the intervention. As expected, we found an accumulation of MES during the passage of the stenosis with guide wires and catheters. During surgery, significantly fewer MES were found than during CAS. Similar findings have already been described elsewhere [5, 6, 11]. Thus DWI lesions and MES were observed more frequently in CAS than in CEA. However, the fact that there is no clear correlation between the occurrence of DWI lesions and MES suggests that the number of MES does not predict the development of ischemic lesions. This assumption is supported by the fact that the clinical outcome (symptoms lasting more than seven days as a result of stroke, in accordance with the criteria used for stroke in ECST [3] and CAVATAS [2]) did not differ significantly between both groups (CAS: one out of 41, CEA: two out of 88).

In four CAS-patients (9.7 %) DWI lesions were found not only in the territory of the treated artery but also in the territories of the contralateral ICA and the vertebral arteries. In these cases, the source of the emboli must have been proximal to the carotid arteries. We did not find any DWI lesions outside the territory of the treated artery in the CEA group. In all these four cases the right ICA was treated. To reach the right ICA, the devices must pass the aortic arch proximal to the left common carotid artery as well as the brachiocephalic trunk proximal to the right vertebral artery. Thus, plaque-material that is detached there might embolize vessels in the territory of the left ICA and the vertebrobasilar arteries. This represents an additional risk because, in the context of CEA, an embolic event in a territory that is not supplied by the treated vessel appears to be impossible. Nevertheless, whether the left or the right side was treated, the total number of lesions after CAS did not differ significantly. Thus, a decision in favour of surgery or CAS should not be influenced by the side of the affected artery. However, it is worthwhile to consider the limitations of filter devices placed in the treated vessel, as the three other brain-supplying vessels are not protected against emboli detached from the aortic arch. Whether non-invasive imaging like CT or MRI of the thoracic aorta might be useful to predict an additional risk of embolic lesions for angioplasty and should influence the choice of CAS versus CEA is certainly fertile ground for further research.

The second aim of our study was to examine the clinical validity of sonographic MES by comparison with DWI-findings. We observed no significant correlation between the total number of MES and DWI-lesions in both groups. The MES seem to represent detached emboligenous material, as is suggested in particular by their distribution with respect to the phases of the intervention. However, the occurrence of MES per se did not allow one to distinguish potentially dangerous emboli from harmless ones. Therefore, this method does not appear to be suitable for investigating the risk of an invasive method like CAS or CEA. Our findings are in accordance with a study from Heesewijk et al. [19], who also found no correlation between the results of T2-weighted MRI examinations and intraprocedural TCD when monitoring CAS. Müller et al. [14] described a significant correlation between the number of MES and DWI findings when monitoring 70 CEAs. They also observed a significant difference in the number of MES when comparing patients that had been treated using a shunt and those without using a shunt. In patients where a shunt was used, the number of MES was more than two times as high as in the other group. However, the number of DWI lesions did not differ between the groups, indicating that the number of MES alone does not seem to be a valuable criterion with which to evaluate the risk of intervention.

The total number of MES correlates with the outcome after CEA in one study [18]. Other investigators did not find such a correlation [4–8]. In some of these trials however there was a correlation between clinical outcome and MES occurring during particular phases of the intervention [4, 7, 8]. But if the total number of MES cannot independently offer a measure for the risk of intervention, it is not possible to compare different interventional procedures by this method.

In conclusion, the value of TCD emboli detection has probably been overestimated as a method for comparing interventional strategies. DWI studies, including volumetric evaluation, should serve as an additional surrogate endpoint of further studies to enable an objective comparison of both methods. Moreover, such an imaging modality could also be used to compare different angioplastic techniques, including the use of filter devices that are nowadays commercially available in various forms.

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