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# Color Doppler, power Doppler and B-flow ultrasound in the assessment of ICA stenosis: Comparison with 64-MD-CT angiography

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**Abstract** The purpose of this study is to investigate the diagnostic potential of color-coded Doppler sonography (CCDS), power-Doppler (PD) and B-flow ultrasound in assessing the degree of extracranial internal carotid artery (ICA) stenosis in comparison to CT-angiography (MD-CTA). Thirty-two consecutive patients referred for CTA with 41 ICA-stenoses were included in this prospective study. MD-CTA was performed using a 64 row scanner with a CTDIvol of 13.1 mGy/cm. In CTA, CCDS, PD and B-flow, the degree of stenosis was evaluated by the minimal intrastenotic diameter in comparison to the post-stenotic diameter. Two radiologists performed a quantitative evaluation of the stenoses in consensus blinded to the results of ultrasound. These were correlated to CTA, CCDS, PD and B-flow, intraoperative findings and clinical follow-up. Grading of the stenoses in B-flow ultrasound outperformed the other techniques in terms of accuracy with a correlation coefficient to CTA of 0.88, while PD and CCDS measurements yield coefficients of 0.74 and 0.70. Bland-Altman analysis additionally shows a very little bias of the three US methods between 0.5 and 3.2 %. There is excellent correlation (coefficient 0.88, CI 0.77–0.93) with 64-MD-CTA and B-flow ultrasound in terms of accuracy for intrastenotic and poststenotic diameter. Duplex sonography is useful for screening purposes.

**Keywords** Internal carotid artery · Multidetector CT angiography · Color-coded · Doppler sonography · Power Doppler · B-flow ultrasound

## Introduction

A reliable differentiation of a high grade stenosis and occlusion in preoperative diagnostics is relevant for the therapy of internal carotid artery stenoses [1–7]. The results of the "North American Symptomatic Carotid Endarterectomy Trial" (NASCET) and the "European Carotid Surgery Trial" ECST [8, 9] have shown that symptomatic patients with high grade (70–90 %) stenoses of the internal carotid artery (ICA) do profit from carotid endarterectomy (CEA). In the guidelines of the American Heart Association and the Executive Committee for the Asymptomatic Carotid Atherosclerosis Study [10, 11], CEA is also recommended as the method of choice for the treatment of asymptomatic patients with high grade stenoses of the ICA. But also the morphology of the stenosis, especially the detection of

ulcerated plaques and thrombi, is crucial for the planning of interventional treatment [1, 2, 5, 7]. The selective intraarterial DSA is a reference standard for the grading of stenoses [1, 2, 12–16]. For the evaluation of stenosis morphology, other imaging procedures such as vascular ultrasound, CTA or MRA can contribute information additional to intraarterial DSA [3, 12, 13, 20]. As a generally available non-invasive imaging method, vascular ultrasound has gained a high importance as first line screening modality as well as for preoperative diagnostics in ICA stenoses. A drawback is that the assessment of filiform stenoses of the ICA can be very difficult due to hemodynamic parameters and partially highly restricted flow [6, 12, 13, 16, 21–24]. Also, dense calcifications can reflect the ultrasound and thus cancel the depiction of the vessel lumen.

B-flow is a new digital vascular ultrasound technique. B-flow is based on a digital subtraction principle. Up to four encoded pulses are delivered along a vector in a defined time interval. The echo sequences obtained comprise an echo signal with a certain intensity, the echo amplitude, for each pixel. Only the coded echoes are analyzed and thus, interference echoes are eliminated. A signal amplitude that is adequate for imaging in B scan is attained using a pulse compression technique. The echo signals of an image line are subtracted one from another so that only the amplitude signal for a reflector, like that for flowing erythrocytes, are imaged in the time interval between two pulses. Compared to the intra-arterial DSA, only the flowing parts but not the stationary structures (e.g., connective tissue, muscles, vessel wall) are imaged. Lines in the one direction and dots in the other indicate direction indicate the direction of flow. The signal amplitude and consequently the brightness of the echoes increases with the flow rate (brightness

mode). The background can be added for better orientation. However, flow velocities cannot be determined [4].

The aim of our study was to compare established vascular US modalities such as CCDS (color-coded doppler sonography), PD (power Doppler) and B-flow in the evaluation of high-degree extracranial ICA stenoses and ICA occlusion. Our expectation was that the improved depiction of flowing blood and the reduction of interference echoes would make a more accurate measurement of the vessel lumen and thus a precise grading of the stenosis possible. The results were correlated with CTA, intraoperative findings and clinical follow-up.

## Materials and methods

### Patients

Vascular ultrasonography (US) and multislice CT angiography (MD-CTA) were performed in 32 consecutive patients between 53 and 84 years of age (mean: 71 years) with suspected stenosis or complete occlusion of the ICA who had been referred for CT angiography. Nine of these patients had a bilateral stenosis. 17 patients suffered from neurological deficits in the form of transitory ischemic attacks, with partially hemiplegic symptoms. Cardiovascular risk factors were arterial hypertension in 19/32, diabetes mellitus type II in 10/32, hyperlipoproteinemia in 17/32 and long-term nicotine abuse in 19/32 patients.

US examinations were included in the prospective study over a period of 13 months from September 2004 to September 2005. US grading of the carotid stenosis was performed in accordance with the principles of the

**Fig. 1** Graphical representation of the statistics of stenoses and occlusions
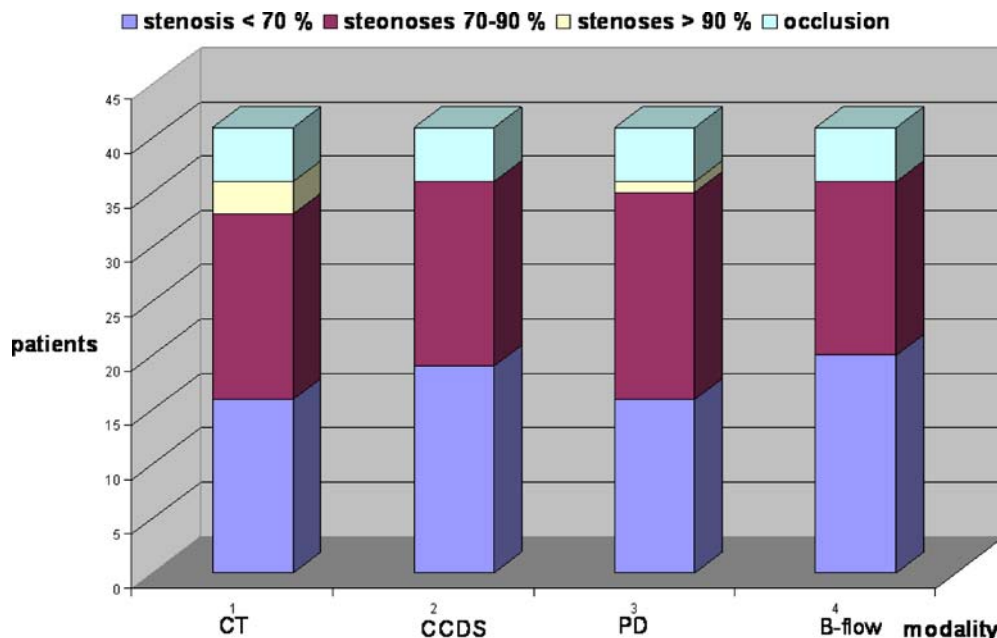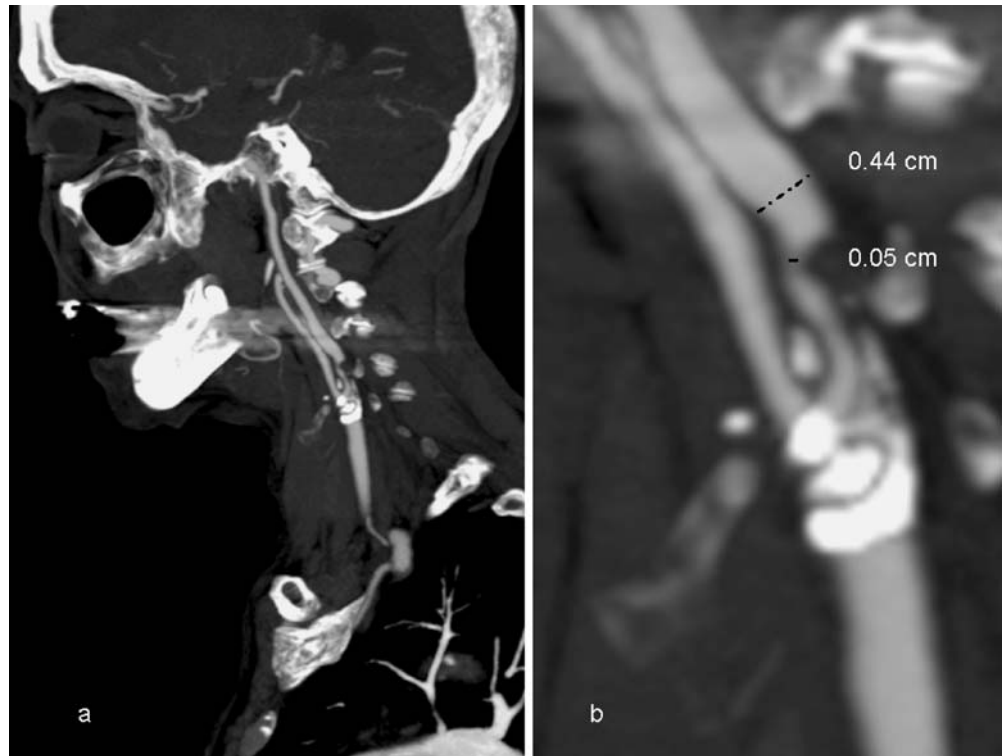
**Fig. 2** High grade ICA stenosis (80–90%) with calcifications in the bulb (**a**). CTA demonstrated a minimal intrastenotic diameter of 0.05 cm and a poststenotic diameter of 0.44 cm (**b**)



consensus meeting on quantifying stenosis of the extracranial carotid artery [5].

In these patients referred to our radiology division to have a MD-CTA using commercially available equipment, a supplementary vascular US investigation with a high-resolution multi-frequency linear probe was conducted with the modalities of CCDS, PD, and B-flow within 48 hours before or after CTA.

All patients were referred after a neurological consultation and gave written informed consent to MD-CTA. The



**Fig. 3** Post-procedural volume rendering technique image of a preoclusive ICA stenosis, same patient as shown in Fig. 5

study was approved by the local ethics committee. In all cases, the investigations to be performed were discussed beforehand in an interdisciplinary colloquium which also discussed the results and the interventional procedure.

MD-CTA

The patients were examined using a standard protocol with a 64 detector CT scanner (Somatom Sensation 64, Siemens Medical Systems, Forchheim, Germany). Collimation and table feed were $64 \times 0.6$ mm, rotation time 0.33 s, pitch 1, slice thickness 0.75 mm, reconstruction interval 0.5 mm. Tube voltage was set to 120 kV, exposure time/tube current product was 200 mAs. The resulting $CTDI_{vol}$ for this protocol was 13.1 mGy/cm.

The contrast agent was injected into an antecubital vein as a bolus using a dual head power injector with a flow rate of 5 ml/s. 120 ml Solutrast (Bracco) with an iodine concentration of 300 mg/ml was applied followed by 50 ml saline. The appropriate scan delay after contrast agent application was determined by semiautomatic bolus tracking. A threshold of 100 HU was selected for the tracking ROI. The imaged volume included the entire carotid arteries from their origin to the circle of Willis. The acquisition direction was caudo-cranial.

For the detection of stenoses, thin slice maximum intensity projections with an increment of 3 mm were reconstructed. For stenosis quantification, stacks of 1 mm thick axial slices were then reconstructed using a soft
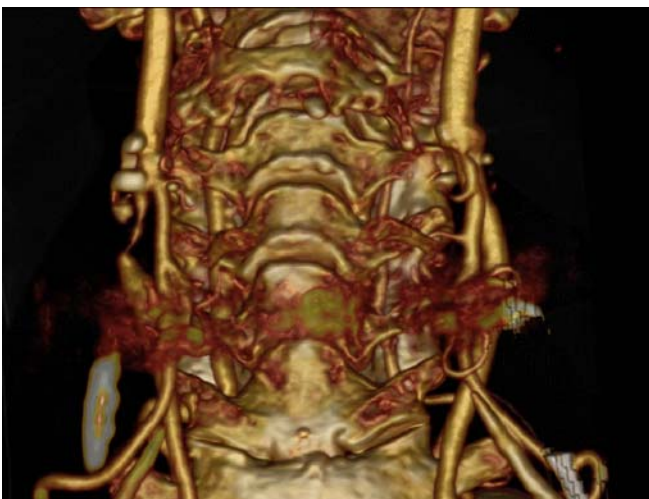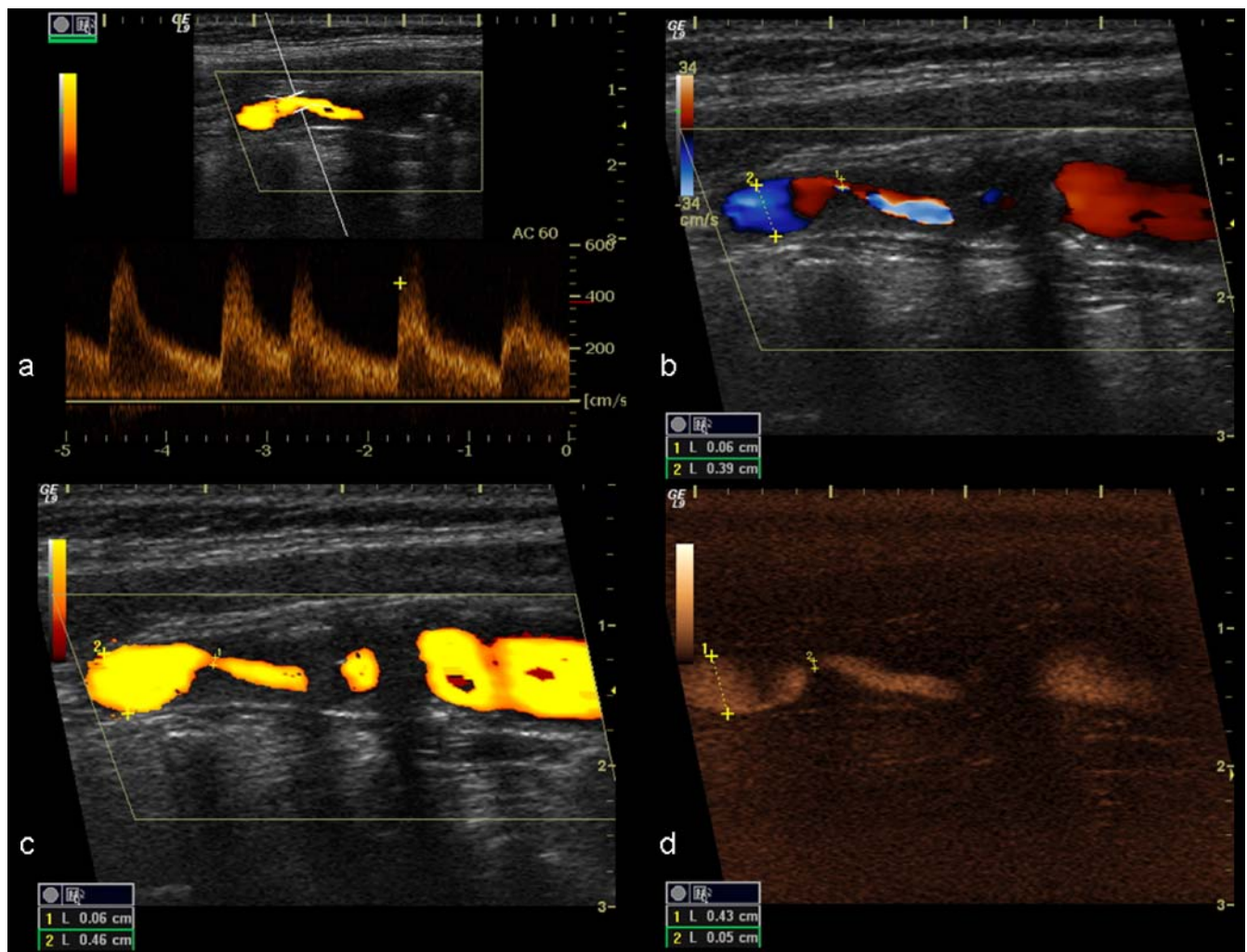
**Fig. 4** Symptomatic 68-year-old patient with diabetes mellitus and hyperlipoproteinaemia same patient as shown in Figs. 2 and 3. (**a**) PD, shows a high-degree stenosis of the ICA with maximal systolic flow velocity of about 600 cm/s. (**b**) CCDS detected a minimal intrastenotic diameter of 0.06 cm and a poststenotic diameter of 0.39 cm, indicating a diameter stenosis of 85%. (**c**) Partial intrastenotic flow detection with PD. PD detected a minimal intrastenotic diameter of 0.06 cm, and a poststenotic diameter of 0.46 cm, corresponding to a 87% stenosis. (**d**) B-flow shows the extent and the morphology of the stenosis with less flow and detected a minimal intrastenotic diameter of 0.05 cm, and a poststenotic diameter of 0.43 cm, indicating an 88% stenosis

convolution kernel (B20f). CT angiograms were analyzed according to NASCET criteria with a fixed window setting (center 1000 HU, width 400). The degrees of stenosis were computed from measurements on multiplanar reconstructions orthogonal to the vessel course.

Vascular US

Two examiners independently performed vascular ultrasound examinations of the extracranial vessels by means of CCDS, PD and B-flow with a multifrequency linear probe (9–12 MHz). The ultrasound device (Logiq 9, GE Medical Systems, Milwaukee, Wisc.) features a high performance processor and allows the documentation of dynamic image sequences in cine mode by a digital frame buffer. This was used to perform a comparative assessment between CCDS, PD and B-flow.

The flow parameters were selected depending on the Doppler shift. The wall filter was 100 Hz to 150 Hz on average, the pulse repetition frequency (PRF) was adjusted <1000 Hz (in most patients 500 Hz, depending on the flow characteristics) which were substantially diminished in poststenotic vessel segments. The color gain was selected just as high as it is necessary to avoid overwriting artifacts (i.e., color pixels outside the perfused lumen of the vessel). Additionally, an automatic image gain optimization could be selected. A transmitter output of 100 %, an average image correlation and an average image rate were chosen for all ultrasound modalities employed.

Besides evaluating the flow with CCDS and recording the pre-stenotic, intra-stenotic and post-stenotic Doppler

**Fig. 5** High degree of ICA stenosis without calcifications in the bulb (**a**). CTA demonstrated a minimal intrastenotic diameter of 0.12 cm and a poststenotic diameter of 0.48 cm, corresponding to a 75% diameter stenosis (**b**)
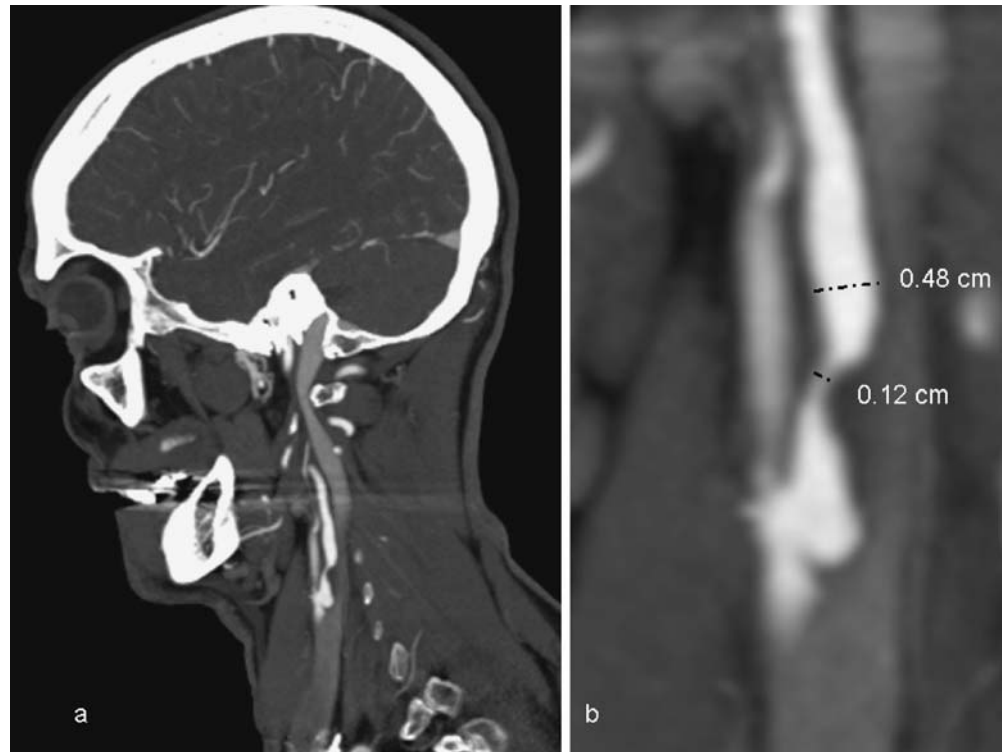
spectra, also longitudinal and transverse scans were documented with PD and B-flow in cine sequences. In order to facilitate the comparison between CCDS, PD and B-flow, the bulb of the ICA was evaluated in centimeter segments [6]. With a flow detection adjusted to be as free of artifacts as possible, we measured the diameter of the ICA stenosis from the still detectable prestenotic segment to the still detectable post-stenotic segment. For all modalities a transmitting power of 100 percent, a medium frame correlation and frame rate were selected. A digital image memory documents dynamic image sequences in cine mode enabling comparison of CCDS, PD and B-flow data simultaneously. All cine loop data sets were later evaluated in consensus by two radiologists who both had extensive experience in interpreting vascular ultrasound scans. Only one of them performed US examinations within this study. Evaluation of the US data sets involved ascertaining flow characteristics to discriminate between high-degree stenosis or occlusion and measurements of the diameter of the stenosis. US image interpretation was performed by investigators who were not aware of the MD-CTA results.

Statistics

We performed the following statistical analyses:

– We computed elementary statistics (mean value and standard deviation).

– Correlation coefficients and regression equations were calculated and

– Bland Altman Plots were created for the comparison of the degrees of stenosis determined in the different ultrasound methods and CTA.

## Results

In our study population of 32 patients, 36 cases of ICA stenosis and 5 cases of ICA occlusion were diagnosed by MD-CTA. A graphical representation of the statistics of stenoses and occlusions is shown in Fig. 1. All patients with occluded ICA were diagnosed correctly by CCDS, PD and B-flow. In all patients with ICA stenosis, it was possible to appraise intra-stenotic and post-stenotic blood flow using B-flow, even in stenoses with diameter narrowing less than 1 mm. Tortuous vessels were partially difficult to assess and calcified plaques sometimes hampered the examination due to shadowing (Figs. 2 and 3).

In 32 patients, measurements were possible with all US modalities. Usually ICA stenoses could be imaged in their diameter extents with B-flow just about as well as with MD-CTA, while the deviations were larger for CCDS and PD (Fig. 4). If the flow parameters were adapted to the high intra-stenotic flow, the diameter of the ICA stenosis was overestimated. If flow parameters were optimized to the low post-stenotic flow, the diameter of the stenoses in CCDS and PD did not correspond well with the measured diameters in CTA due to blooming artefacts of the
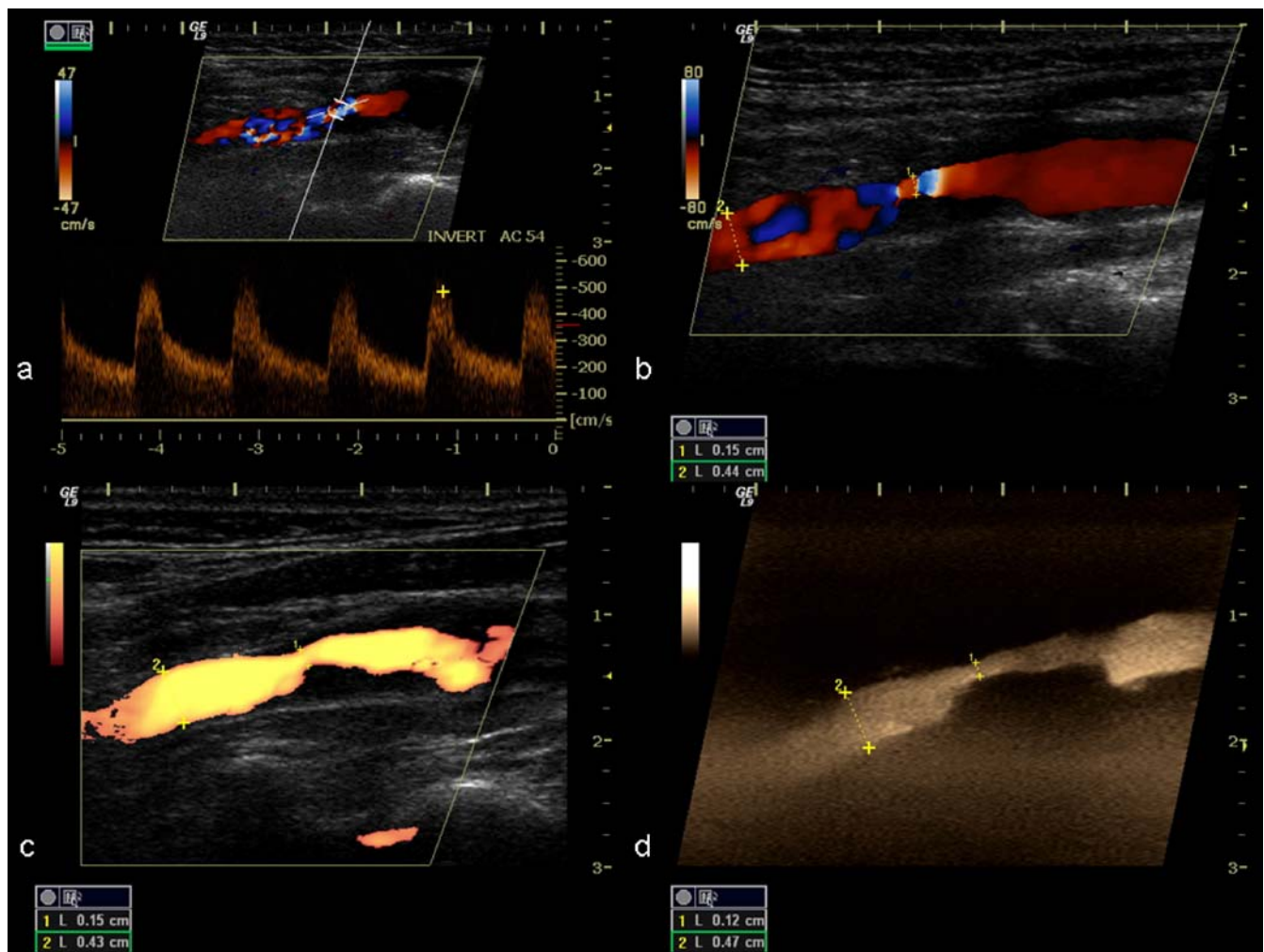
**Fig. 6** Symptomatic 73-year-old patient with diabetes mellitus same patient as shown in Fig. 5. (**a**) CCDS shows a high-degree stenosis of the ICA with a maximal systolic flow velocity of about 500 cm/sec. (**b**) CCDS detected a minimal intrastenotic diameter of 0.15 cm and a poststenotic diameter of 0.44 cm, i.e., a 66% stenosis. There is an incomplete flow detection with intrastenotic aliasing in CCDS. (**c**) PD detected a minimal intrastenotic diameter of 0.15 cm and a poststenotic diameter of 0.43 cm, corresponding to a 65% stenosis. (**d**) B-flow shows the extent and the morphology of the stenosis with soft plaques and without flow artefacts compared to the CTA. B-flow detected a minimal intrastenotic diameter of 0.12 cm and a poststenotic diameter of 0.47 cm, i.e., a 74% stenosis

turbulent flow in ultrasound letting the lumen seem larger and on the other hand blooming artefacts due to calcifications in CTA narrowing the depicted lumen (Figs. 5 and 6).

The analysis of the measurements for the intrastenotic and poststenotic diameters and the measured degree of stenosis according to the NASCET criteria showed differences for CCDS, PD and B-flow techniques compared to

**Table 1** Averages, standard deviations and ranges for intra- and poststenotic diameters and degrees of stenosis determined in CT angiography (CTA), color-coded doppler sonography (CCDS), power Doppler (PD) and B-flow ultrasound

|  | CTA | CCDS | PD | B-flow |
|---|---|---|---|---|
| Intrastenotic diameters (cm) | 0.15±0.06 | 0.16±0.07 | 0.15±0.07 | 0.16±0.07 |
| Range | 0.04–0.30 | 0.06–0.35 | 0.02–0.32 | 0.04–0.31 |
| Poststenotic diameters (cm) | 0.51±0.15 | 0.51±0.13 | 0.48±0.12 | 0.48±0.15 |
| Range | 0.26–1.27 | 0.28–1.15 | 0.23–0.95 | 0.25–1.20 |
| Degree of stenosis (%) | 70.01±13.27 | 68.20±13.15 | 69.47±12.49 | 67.22±13.47 |
| Range | 42.85–92.85 | 33.96–89.56 | 40.38–91.30 | 38.00–90.00 |

**Fig. 7** Scatter plot of the minimal intrastenotic diameters measured with CCDS, PD and B-Flow related to MD-CTA
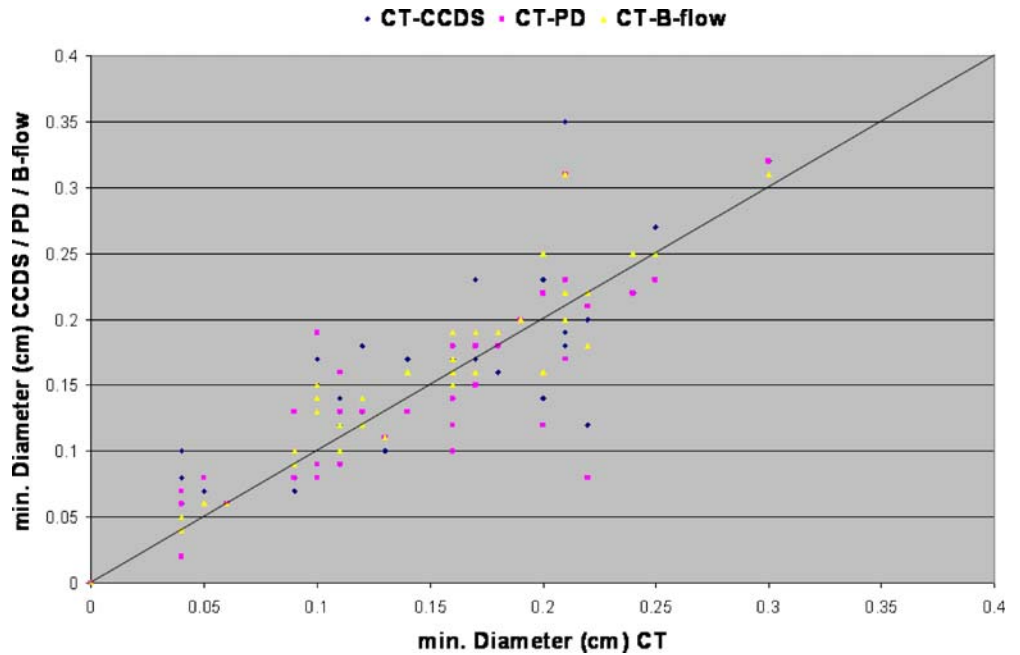
MD-CTA. The values are given in Table 1. The respective scatter plots for the measured diameters and the degree of stenosis in the ultrasound techniques and in CTA are shown in scatter plots in Figs. 7, 8, 9.

The regression equations, the correlation coefficients and the level of significance for the stenosis grade determined in the different ultrasound methods in comparison to CTA are given in Table 2, and Figs. 10, 11, 12 show the respective Bland-Altman plots.

The plots show that the degree of stenosis determined in B-flow mode correlates best with CTA with a coefficient of

0.88, while PD and CCDS measurements only yield correlation coefficients of 0.74 and 0.70, respectively. Figure 1 shows that these differences can be observed even if defined diagnostic strata are used.

The intraoperative findings correlated well with the degree of stenosis in CTA. In cases of high degree stenoses diagnosed with CTA and ultrasound intraoperatively no occlusions were found. All occlusions were diagnosed correctly by all US methods. In cases with an occlusion diagnosed with CTA and ultrasound the clinical follow-up showed no significant neurological deficits in the form



**Fig. 8** Scatter plot of the post-stenotic diameters measured with CCDS, PD and B-Flow related to MD-CTA
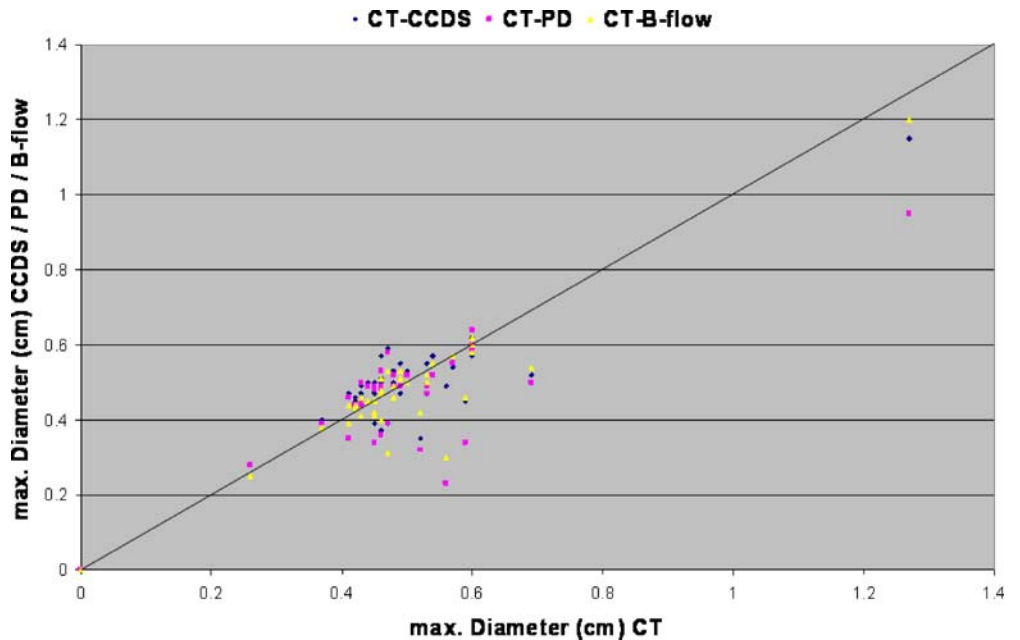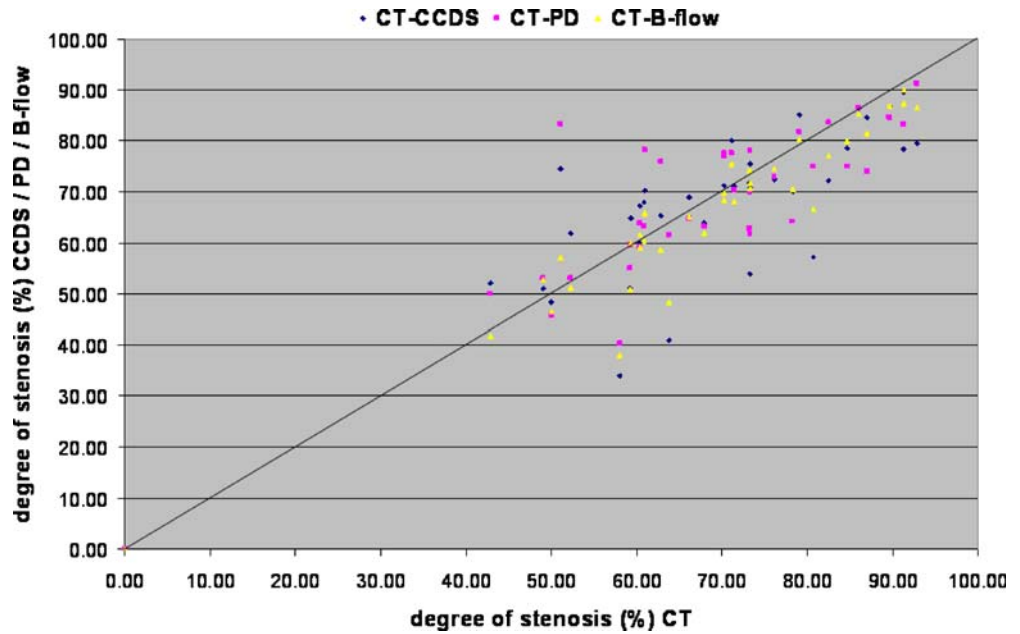
**Fig. 9** Scatter plot of the degrees of stenosis measured with CCDS, PD and B-Flow related to MD-CTA



of transitory ischemic attacks or partially hemiplegic symptoms.

## Discussion

Vascular US is usually the initial modality used to evaluate high grade ICA stenoses [1–7]. Determining the degree and morphology of stenosis is very important for planning surgery [3, 4, 7, 13, 14, 28–30]. The potential benefit of an intervention can be forfeited when a preocclusive ICA stenosis is overestimated as an occlusion, and the risk of a stroke recurrence remains. Additionally, if collateral flow phenomena accompanying an ICA occlusion are misinterpreted as residual ICA flow, unnecessary diagnostic tests with the potential to increase risks might be undertaken. In some cases, even an unsuccessful operation may be performed. This is why new vascular ultrasound techniques have been evaluated to establish the extent to which minimal residual flow phenomena that are still present with preocclusive ICA stenosis can be reliably identified in comparison to MD-CTA, which is considered the standard by many authors [3, 5–7, 24, 25, 32, 33, 41–43]. In our study, we chose MD-CTA as the reference method because

of its high local spatial resolution, although its limitations especially in the presence of dense calcifications of high grade stenoses have not been studied extensively.

In cases of preocclusive stenoses it is indispensable to establish the intra-stenotic and post-stenotic flow in order to differentiate an occlusion with partial re-canalisation [3, 6, 7, 15], and all the ultrasound techniques under investigation reliably detected residual flow in the present study. However, CCDS is of limited usefulness for detecting preocclusive stenoses because intra-stenotic flow acceleration leads to reverberation artifacts. In the post-stenotic segment, low flow volumes can be detected only with difficulty [7, 35]. In addition, the angle-dependency of CCDS does not only influence the velocity measurement, but also the simultaneous establishment of the pre-, intra- and post-stenotic flow in the longitudinal scan, in particular for tortuous vessels [28, 34, 35]. Difficult conditions such as a carotid bifurcation with relatively cranial location, a kinking of the vessel or distinct calcification in the vessel wall can complicate the situation and lead to wrong diagnoses [4–7, 16].

PD is an US technique that is very much less angle-dependent than CCDS. It has been shown in comparative studies that PD has diagnostic advantages over CCDS,

**Table 2** Regression equations, correlation coefficients and significance levels for the regression analysis of color-coded doppler sonography (CCDS), power Doppler (PD) and B-flow ultrasound with reference to CT angiography

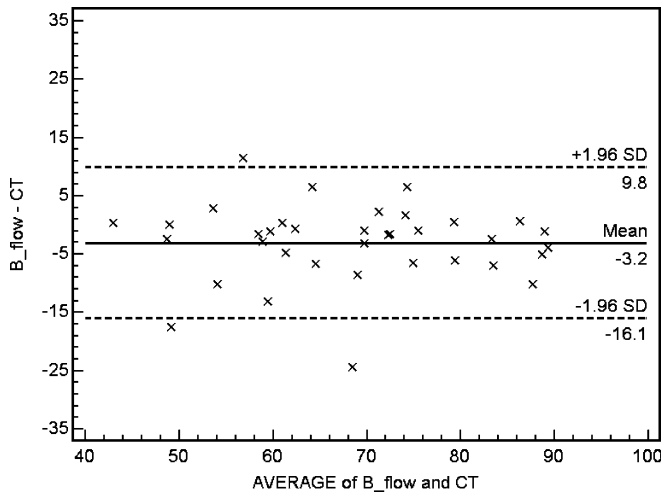|  | CCDS | PD | B-flow |
| --- | --- | --- | --- |
| Regression equation | Y=0.69 X+19.9 | Y=0.70 X+20.7 | Y=0.86 X+6.2 |
| Correlation coefficient | 0.6953 | 0.7393 | 0.8750 |
| 95% confidence interval | 0.4753–0.8334 | 0.5425–0.8591 | 0.7670–0.9348 |
| Level of significance | P<0.0001 | P<0.0001 | P<0.0001 |

**Fig. 10** Degree of stenosis measured in CTA and in B-flow ultrasound compared in a Bland-Altman plot. The mean difference is 3.2% with limit of agreement at +16.1 and −9.8%
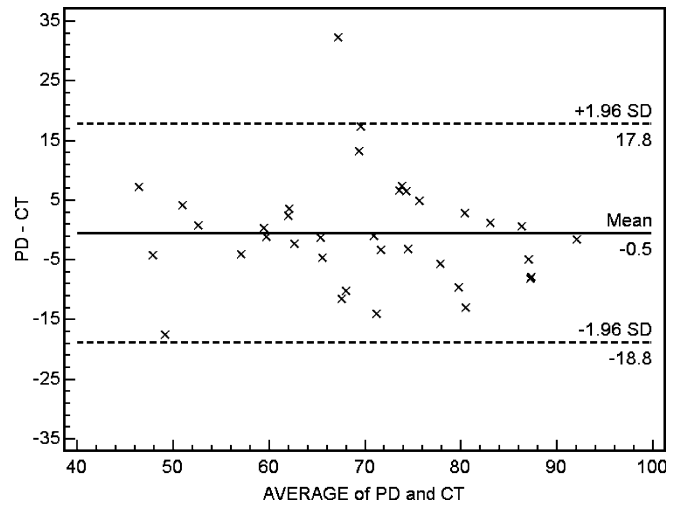


**Fig. 12** Degree of stenosis measured in CTA and in PD ultrasound compared in a Bland-Altman plot. The mean difference is 0.5% with limit of agreement at +18.8 and −17.8%

especially in detecting intra-stenotic and post-stenotic flow phenomena in high-degree ICA stenoses [7]. Overestimation of the vessel lumen and underestimation of the diameter of a stenosis as a result of pulsation and blooming artefacts known from CCDS also occurs in PD in stenoses. Nevertheless, comparative studies indicate that sonographic diagnostics of high-degree stenoses are improved using PD [27, 30].

B-flow enables markedly better angle-independent flow detection on the basis of amplitude imaging that does not depend on the Doppler principle [8, 26]. B-flow is a new technique that extends the resolution, frame rate, and



**Fig. 11** Degree of stenosis measured in CTA and in CCDS ultrasound compared in a Bland-Altman plot. The mean difference is 1.8% with limit of agreement at +22.0 and −18.4%

dynamic range of B-mode to simultaneously image blood flow and tissue. B-flow relies on coded excitation to boost weak signals from blood scatters and on tissue equalization to simultaneously display flowing blood and tissue without threshold decision and overlay. B-flow achieves high resolution with broadband B-mode pulses and high frame rate by using small packet sizes. B-flow cine-loops demonstrate a resolution and frame rate three times higher than color flow. This, together with over 60 dB of display dynamic range, is able to image haemodynamics and vessel walls with clarity.

B-flow provided sonographic diagnosis of ICA stenoses with high diagnostic reliability in our studies. Although all ultrasound techniques reliably detected residual flow in the present study, compared to widely-used US techniques such as CCDS and PD, B-flow additionally makes it possible to detect the pre-stenotic, intra-stenotic and post-stenotic flow simultaneously, especially in elongated vessels. This is also facilitated by the fact that high-velocity and low-velocity flow phenomena are registered at the same time without flow artefacts [9]. The grade of stenosis can be assessed in comparison to the MD-CTA according to the NASCET criteria. The intra-stenotic and post-stenotic flow can be imaged with B-flow if existing vessel wall calcifications are not circular. In cases of marked calcifications, the B-flow allows intra-stenotic flow detection of stenoses without aliasing and without the blooming flow artifacts of CDDS and PD.

In markedly elongated vessels, a high bifurcation or kinking, the diameter of the stenosis cannot be appraised with certainty. It is then easiest to detect the flow in the kinking as artifact-free and as angle-independently as possible with B-flow. If there also is a stenosis, flow and vibration artifacts are avoided in addition. On the other hand, these can also contribute to diagnostics as indirect
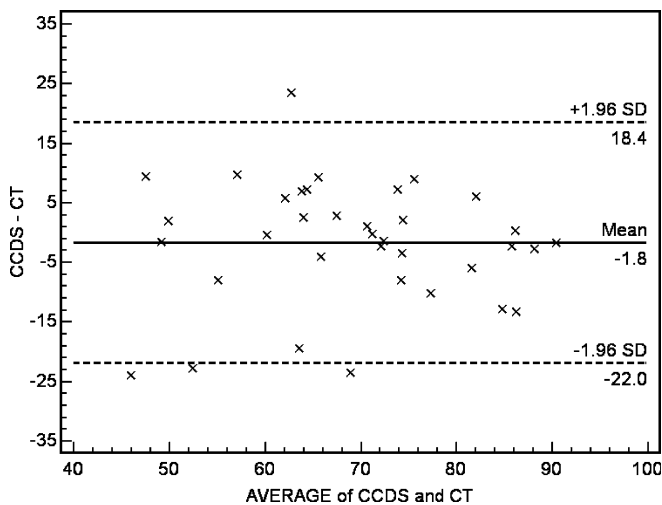
criteria of stenosis in the CCDS and the power Doppler provided flow parameters are optimised. Nevertheless, these artifacts make it more difficult to detect the extent of stenosis and to appraise the degree of local and distal stenosis.

The limitations of the present study are the lack of comparison with intra-arterial DSA. Moreover, the range of a preocclusive stenosis and its diameter can only be established to a limited extent by means of the various ultrasound methods considering different positions, patient motion and special anatomical situations. This requires optimal setting of flow parameters for the different US techniques. Consequently, the diameter measurements, too, depend on the investigator. Our own experience indicates that blooming artifacts do not occur in B-flow and that the color coding of the grey tones mostly anticipates the effect of contrast medium enhancement [32]. When there are circular calcifications, all US modalities encounter constraints: in some cases, areas of residual flow can be detected in the B-flow cross-section that can otherwise be demon- strated only after administering US contrast media with the CCDS and PD.

## Conclusion

B-flow represents an improvement for the diagnostics of stenosis of the ICA compared to other ultrasound techniques, offering a more accurate depiction of the vessel lumen. The quantification of the degree of stenosis shows a very good correlation to MD-CTA. However, CCDS remains necessary to quantify flow velocities in order to determine haemodynamic relevance [39, 40].

Ultrasound is an important screening tool for the detection of stenoses of the carotid arteries. Particularly regarding pseudo-occlusions, the results of ultrasound with the detection of residual flow and determination of hemodynamic parameters can often have an impact on surgical planning and add to the information provided by other imaging modalities.

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