Ultrasonography of carotid stenosis

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Abstract

The classification of internal carotid artery stenosis is of great impact. The degree of stenosis is the main criterion for the decision between an invasive or non-invasive treatment of extracranial internal carotid artery (ICA) stenoses. By now the North American Symptomatic Carotid Endarterectomy Trial (NASCET) criteria have been internationally approved for radiological grading. According to NASCET the stenosed lumen is compared with the lumen of the distal internal carotid artery. All ultrasound criteria do have limitations and can therefore cause pitfalls in determining the degree of stenosis using one criterion exclusively. Therefore a multi-parametric grading of stenoses should be favored. The multi-parametric “DEGUM” ultrasound criteria have been revised and a novel differentiation between main (primary) and additional (secondary) criteria has been proposed. Recently a similar consensus was reached by the Neurosonology Research Group (NSRG) of the World Federation of Neurology (WFN). Main criteria include the following: imaging of the stenosis in B-mode sonography; visualization of the stenosis by color-coded imaging of flow; measurement of the maximum systolic flow velocity in the area of greatest narrowing of the lumen; systolic flow velocity measurement in the poststenotic segment; assessment of the collateral supply. Additional criteria include the following: indirect findings of an internal carotid artery stenosis in the common carotid artery; evidence of flow disturbances; end-diastolic flow velocity in the area of greatest narrowing of the lumen; the so-called confetti-sign; the carotid ratio. The main advantage of a multi-parametric grading of ICA stenoses is the synergetic effect of the different single criteria. Combining these ultrasound criteria, neurosonography allows reliable grading of carotid stenoses as a basis for decision making.

Keywords: Carotid stenosis, ICA stenosis, Degree of stenosis, Duplex ultrasonography, Peak systolic velocity, NASCET, ECST.
Introduction

Ultrasonography of the carotid arteries is the modality of choice for triage, diagnosis, therapy and monitoring of patients suffering from atherosclerotic disease. The degree of stenosis is the main criterion for the decision between an invasive (thromboendarterectomy (TEA) or dilatation and stent) or non-invasive treatment of extracranial ICA stenoses. In asymptomatic stenosis the rapid increase in the degree of stenosis is the most important indicator of an increased risk of stroke [1].

NASCET versus ECST

In Germany, as in other European countries, the local diameter narrowing (European Carotid Surgery Trial (ECST) method) was popular [2, 3] whereas in North America the distal diameter of the ICA was taken as denominator (distal diameter narrowing, North American Symptomatic Carotid Endarterectomy Trial (NASCET) method) [4]. According to NASCET the stenosed lumen is compared with the lumen of the distal ICA (Figure 1). By now the NASCET criteria have been internationally approved for radiological grading.

In Table 1 degrees of stenoses measured by NASCET method are compared to the ones of the same stenoses measured by ECST method. The ECST method results in higher degrees of stenosis especially in the range of up to 70% stenosis. That is why the same stenosis can be classified as 50% (NASCET) by a radiologist and 70% (ECST) by an ultrasound investigator.

This is why measuring following the ECST method and recommending carotid surgery following the NASCET criterion of 70% can be a possibility of a malpractice. Therefore it is essential that the different methods used for the classification (either NASCET or ECST) are mentioned in the findings.

Table 1. Classification of the same stenosis measured by NASCET and by ECST.

<table>
<thead>
<tr>
<th>Degree of stenosis</th>
<th>NASCET method</th>
<th>ECST method</th>
</tr>
</thead>
<tbody>
<tr>
<td>30%</td>
<td>50-60%</td>
<td></td>
</tr>
<tr>
<td>50%</td>
<td>70%</td>
<td></td>
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<tr>
<td>60%</td>
<td>75%</td>
<td></td>
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<td>70%</td>
<td>80%</td>
<td></td>
</tr>
<tr>
<td>80%</td>
<td>90%</td>
<td></td>
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</tbody>
</table>

Conversion from ECST to NASCET and vice versa

It is possible to perform a conversion [5] from ECST to NASCET using this formula:

\[
\text{NASCET}\% = \frac{(\text{ECST} - 40)}{0.6}
\]

A conversion from NASCET to ECST is possible by using this formula:

\[
\text{ECST}\% = 40 + 0.6 \times \text{NASCET}\%
\]

Peak systolic velocity as exclusive hemodynamic parameter for the classification of stenosis

Between Europe and North America there was another basic different methodological approach in classification of ICA stenosis. North America classifies stenoses using only one hemodynamic parameter as the primary and only criterion defined in a consensus of the Radiological Society of North America (RSNA) [6].

This only hemodynamic parameter represents the lower limit value of peak systolic velocity (PSV) (Figure 2), which includes any possible findings of stenoses ≥70%. The intention of this methodological approach of the RSNA was not to quantify stenoses in steps of 10% but to dichotomize them in ≥70% or <70%, to dichotomize in invasive such as TEA or non-invasive, conservative therapy. Here the RSNA demands a threshold-PSV that includes all stenoses that are classified ≥70%. For this threshold-PSV different values are published in literature. Moneta et al. analyzed this at a bigger sample [7]. If for stenoses classified 60-99% (NASCET) a threshold-PSV of 200 cm/s was assumed, then the sensitivity was high (93%) and the specificity low (76%) with an accuracy of 84% at which the accuracy was defined as the maximum sum of sensitivity and specificity. If for stenoses 60-99% (NASCET) a threshold-PSV of 300 cm/s was assumed, then the sensitivity was as well high (95%) and the specificity low (78%) with an accuracy of 87%. Assuming a threshold-PSV of 260 cm/s for stenoses of 60-99% (NASCET) the accuracy of 88% has been the highest; meanwhile the sensitivity was 86% and the specificity 91%.

Figure 1. Different methods for grading carotid stenosis. Differentiation between the European Carotid Surgery Trial (ECST) and the North American Symptomatic Carotid Endarterectomy Trial (NASCET).

ECST: Percentage of local diameter reduction: the degree of stenosis (A) is determined in relation to the original lumen (C) of the ICA (A vs. C).

NASCET: Percentage of distal diameter reduction: the degree of stenosis (A) is determined in relation to the distal lumen (B) of the ICA (A vs. B).
Does the approach of peak systolic velocity alone provide a sufficient reliable and reproducible grading of carotid stenoses and valid results?

A consensus for threshold values based on a meta-analysis was published [6]. There are also several publications of correlations between PSV and the degree of stenosis measured by X-ray angiography which have shown substantial scattering of results in all published studies [7-12]. That was the reason for the NASCET group [13] and recently the American Heart Association to not recommend carotid surgery in symptomatic patients if diagnosed only on duplex sonography [14]. A stenosis can be graded following its morphologic effects using the more morphologically orientated angiography or by its hemodynamic effects using the more hemodynamically orientated ultrasonography. Both techniques do have their limitations. This is the reason why there is no perfect correlation between these different approaches. The PSV—for many reasons and no matter what threshold-PSV chosen—is only of limited value if taken alone as well as this criterion is very often in disagreement with the angiographic result.

It is well-known that there are many factors that might influence the PSV, which are briefly described here.

Technical parameters

Technical parameters that can affect the accuracy of carotid ultrasonography results include the Doppler angle, sample volume box, color Doppler sampling window, color velocity scale, and color gain [15].

Doppler angle

At the one hand the angle of insonation can influence the PSV to a critical point (Figure 3), on the other hand errors and different conventions especially occur while positioning the Doppler angle. The measuring of the angle of insonation is needed for converting recorded Doppler frequencies into velocities [16]. The recordings of the highest frequencies in systole reveal from the streamlines with the highest velocities and with the smallest Doppler angle (Figure 3). Due to the cosine function (Doppler equation) the possible error converting Doppler shift to velocity increases with increasing Doppler angle. This is the reason why the variability of velocity estimation is higher if compared to the recorded frequency. In disturbed flow conditions with stream lines that differ from the vessel course it is more difficult to estimate the Doppler angle. This can be done at least fairly well in laminar conditions.

Spectrum analysis

The technical problems of spectrum analysis can also significantly affect the PSV. Due to vortices and flow separation there are low-frequency components as well as high-frequency (velocity) components representing the jet within the typical Doppler spectrum generated by a short stenosis. Underestimation of the PSV can happen due to the too low relative weight of the high-frequency components. Without special filtering this effect would have an even stronger impact [17].

Morphology of the stenosis

An important component of carotid ultrasonography is to adequately document the location, internal characteristics, and surface detail of plaque. Plaque can be simply characterized as homogeneous or heterogeneous. The pathogenetic substrate is a plaque that causes hemodynamic effects due to an area reduction and surface eventually creating emboli or an occlusion. The anatomic correlate for the
hemodynamic effect and the measured flow velocities is area reduction by a stenosis not diameter reduction. The type of stenosis—whether it is a concentric or eccentric—is essential for the relationship between area and diameter reduction [18].

Collaterals
The influence of collateral flow to the PSV is of fundamental importance.

The collateral flow toward the territory supplied by the stenosed artery determines the velocities in a stenosis. The higher the capacity of this collateral network, the less the poststenotic pressure decrease and, consequently, the intrastenotic PSV [19]. Next to the area restriction the resulting pressure drop indicates the PSV. In case of good collateral supply to the irritated territory this pressure drop is smaller. The result is a reduced flow volume and flow velocity in the severely stenosed artery. In contrast, when there is no collateral supply available very high velocities can be recorded from the same degree of stenosis [19, 20].

Velocity in a nearly occluded artery
There is the possibility of the same PSV in a moderate stenosis and a nearly occluded artery [18, 21]. The PSV in a stenosis increases with increasing degree of stenosis but decreases in vessels with near occlusion. In 80%-90% stenoses the highest PSV will be seen. The PSV is lower and variable in cases of stenoses near occlusion [19, 22-24]. That is why this criterion of the intrastenotic PSV alone is no good indicator for the differentiation between a moderately stenosed and a nearly occluded artery.

Looking at all these influencing factors it seems obvious that the approach of PSV in terms of being used as a single simplified diagnostic parameter is not reliable. PSV measurements in a stenosis alone are not sufficient to differentiate a moderate from a severe (≥70% NASCET) stenosis with sufficient clinical reliability. The possibility to combine PSV with further criteria makes it possible to decide whether the measured PSV is the result of a less or more severe stenosis within the scatter range. The advantage of a multiparametric approach is that the diagnostic ultrasound offers the possibility of using both morphological and hemodynamic criteria.

Consequently the NASCET method as the morphologic correlate and the colour coded imaging of flow for the detection of low degree diseases and occlusion have been included into the new intersociety guidelines that were published in Germany [22, 25]. Therefore, these multi-parametric “DEGUM” ultrasound criteria have been revised and a novel differentiation between main (primary) and additional (secondary) criteria has been proposed. The “Neurosonology Research Group (NSRG) of the WFN” has reached a similar consensus recently [12]. Both guidelines point out the importance of a multiparametric approach with main and additional criteria. The differentiation between main and additional criteria is caused by the different reliability of the single criterion.

This multiparametric approach allows a grading of severe stenosis in steps of 10%, so it is possible to differentiate between a stenosis of 70%, 80%, 90% or an occlusion.

The multiparametric approach - Main (primary) criteria

Criterion 1 - B-Mode
Non-stenosing plaques (up to 10% according to NASCET)

Imaging of the plaques is the domain of B-mode sonography in non-stenosing plaques (Figure 4).

B-mode sonography provides important information regarding the presence of plaques and their size, morphology, and classification (Figure 5). In order to determine their size and location it is helpful to scan several longitudinal and transverse planes. In addition to the size and location of a plaque its surface, structure and echogenicity have to be assessed. For follow-ups a documentation of the maximum thickness and length of a plaque should be made. A percentage grading according to NASCET does not make sense.

Criterion 2 - Color coded imaging of flow
Moderate stenoses (20–40% according to NASCET)

This remains the specific field of B-mode imaging in the longitudinal and cross-sectional planes. The reduction of diameter, the thickness and length of the plaque as well as the residual lumen should be measured. In this case color coded imaging of flow is essential to identify the area of greatest narrowing of the ICA lumen.

The color velocity scale is the most important parameter of the carotid ultrasonography color Doppler setup. The color velocity scale is an operator-defined range of velocities that requires adjustment, analogous to the window width and level of a gray-scale image. It is not synonymous with the pulse repetition frequency (PRF), but the PRF is related to the velocity scale setting, so that increasing the velocity scale increases the PRF and vice versa [26-29]. The image frame rate may appear slow if a very low color velocity scale is applied, since the PRF decreases and the time between transmit pulses in a pulse packet increases [26].

If the velocity of blood flow exceeds ½ the PRF (Nyquist limit), then the direction and velocity are inaccurately displayed and flow appears to change direction (aliasing).

Aliasing
The maximum clearly measurable Doppler frequency shift (Fmax) referred to as the Nyquist frequency corresponds to half the PRF:

\[ F_{\text{max}} = \frac{PRF}{2} \quad \text{PRF} = 2 \times F_{\text{max}} \]
Figure 4. Wall thickening over an extended vessel segment. Additionally circumscribed plaques with echogenic spots and distinct acoustic shadowing.

Figure 5. Isolated, long hypoechoic plaque.

Figure 6. Color coding with the aliasing effect.

If the Doppler frequency is greater than half the PRF, it cannot be precisely identified.

Consequently the peaks of the spectral curves are cut off and displayed again below the zero line with apparently reversed flow direction (Figure 6). This "incorrect" registration, the so-called aliasing phenomenon is also familiar from the cinema: the spoke of a wheel of an accelerating carriage initially turn in the direction of movement, then appear to stop moving (Nyquist limit), then to turn in the opposite direction, and finally with increased acceleration they again turn in the direction of movement. These changes depend on whether the number of revolutions of the wheel is greater or less than the frame rate (which in this case represents the Nyquist limit).

In color-coded duplex sonography the frequencies which exceed the aliasing threshold are color coded with the colors of the opposing half of the color scale (Figure 7 and Figure 8). The aliasing phenomenon can be avoided, up to a certain limit, by raising PRF.

Aliasing can be advantageously used to identify the area of greatest narrowing of the ICA lumen. The local flow velocity acceleration is visible by the local aliasing occurring in the area of greatest narrowing of the lumen (at appropriate device setting). Aliasing can be advantageously used to demonstrate high or low flow and turbulence. If the color velocity scale is set below the mean velocity of blood flow, aliasing throughout the entire vessel lumen makes it impossible to identify the high-velocity turbulent color jet associated with a right stenosis. Conversely, if the color velocity scale is set significantly higher than the mean velocity of blood flow, aliasing may disappear, resulting in a missed stenosis (Figure 9).

Therefore the adjustment of the appropriate color scale in a carotid artery stenosis is very important. Color Doppler image obtained with the color scale set too low (e.g. 4 cm/s) shows aliasing in the entire segment of the ICA. On the other hand, a color Doppler image obtained with the color scale set too high (e.g. 115 cm/s) shows no
aliasing. Therefore—at a too low color scale—we gradually increase the aliasing threshold (PRF) to a remaining aliasing phenomenon only at a circumscribed segment. Using this procedure we can identify the area of the greatest narrowing of the ICA lumen. Color Doppler image obtained with the optimal color scale setting shows the region of highest velocity, which corresponds to the narrowest segment of the ICA. Velocity sampling should be performed at this region.

**Figure 7.** Color coding with the aliasing effect. The aliasing effect (shown here in the case of a high-grade stenosis) is characterized by a transition of the orange and yellow shades at one end of the color scale to light blue and green shades at the other end of the scale (b) [30].

**Figure 8.** Color coding in the case of a true change in flow direction and comparison of true change in flow direction versus aliasing. Folding over or wrapping around of the color as a result of a change in flow direction (distal to a medium-sized plaque). The transition of red to dark blue (a) proceeds through a black line which represents a velocity of 0 cm/s [30].

**Criterion 2 - Color coded imaging of flow**  
**Moderate stenoses (50–60% according to NASCET)**

In these stenoses a combination of B-mode imaging, color flow, local velocity increase should be performed for grading. In general, threshold-PSV is below 230 cm/s. In moderate stenoses collateral flow cannot be found.

Grading of carotid stenosis by diagnostic ultrasound should be primarily based on morphological information.
(B-mode, color coded imaging of flow) in low to moderate degrees of stenosis. In addition the degree of narrowing, plaque thickness, plaque length, and residual lumen should be reported.

**Criterion 2 - Color coded imaging of flow**

*High grade, hemodynamically relevant stenosis (>70% according to NASCET)*

In high grade stenoses, the combined hemodynamic criteria, such as increased PSV, end-diastolic velocity and the “carotid ratio” (ratio of internal to common carotid artery PSV) are typically the method of choice (Figure 10).

**Criterion 2 - Color coded imaging of flow**

*Occlusion of ICA*

Color coded imaging of flow is important as a guide for velocity measurement and is essential for differentiating occlusion from stenosis (Figure 11).

**Criterion 3 - Stenotic PSV**

The PSV should be measured in the area of greatest narrowing. This area of greatest narrowing should be determined using color coded imaging of flow with adjustment of the PRF (aliasing). The insonation angle should be below 60° (Figure 3).

The angle correction has to be set to the direction of jet flow. If the stenosis can not be shown directly due to an acoustic shadow, the Doppler recording occurs in the jet flow immediately poststenotic (Figure 12).

In a degree of stenosis below 40% according to NASCET the intrastenotic average-PSV is ≤ 160 cm/s, in case of classification of 50% (NASCET) the average-PSV is 210 cm/s. In case of 60% (NASCET) the average-PSV is 240 cm/s, in case of a stenosis of 70% (NASCET) the threshold-PSV is 230 cm/s and the average-PSV 330 cm/s. In a stenosis of 80% (NASCET) the average-PSV is 370 cm/s. In 80-90% stenoses the highest intrastenotic PSV will be seen. In near occlusion PSV is lower and variable [19, 22-24, 31].

**Criterion 4 - Poststenotic PSV**

A further main criterion represents the poststenotic PSV in the vessel section distal to the disturbed flow field. It is recommended that the poststenotic flow velocity distal to the flow disturbances is examined, in which a reduction of velocities (comparison with the unaffected contralateral side) allows additional grading within the category of severe stenosis. Irrespective of the intrastenotic PSV we can assume that in a considerable reduction of poststenotic velocity (e.g. poststenotic PSV <30 cm/s) and signal pulsatility the reduction of ICA diameter is about 90% and the residual lumen is less than 1mm. The extent of the reduction of poststenotic PSV correlates with the reduction of flow volume. The differentiation between 70% and 80% to 90% stenosis (NASCET) is supported by the degree of reduction of poststenotic PSV. Using PSV values alone, this differentiation is not possible.

In a degree of stenosis up to 70% (NASCET) the maximum poststenotic velocity is more than 50 cm/s.

In a degree of stenosis at 80% (NASCET) the maximum poststenotic velocity is below 50 cm/s.

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**Figure 10. High grade stenosis.** Prestenotic in the CCA (a): reduced systolic and end-diastolic flow velocity; increased pulsatility (reduced end-diastolic flow velocity due to the increase of the flow resistance). In the stenosed region (b) significantly increased PSV (aliasing). Distal to the stenosis (c) considerable amount of inverse frequency components. With color coding red and blue shades (separated by a black line, indicate disturbed flow). In the poststenotic region (d) reduced flow velocity.
In a degree of stenosis at 90% (NASCET) the maximum poststenotic velocity is below 30 cm/s.

Criterion 5 - Collaterals

In order to maintain blood circulation in the brain in cases of high-grade stenoses or occlusions of cerebral arteries, numerous collateral connections between the arteries are available. These are supported by a compensatory hyperperfusion in their feeding arteries.

Typical collateral systems are:
- Collaterals of ophthalmic artery.
- Collaterals of the anterior communicating artery.
- Collaterals of the posterior communicating artery.
- Collaterals of the cerebral convexity (leptomeningeal anastomoses).

The most important collateral artery between the external and internal carotid arteries is the ophthalmic artery. In this system, collateral circulations are formed between the terminal branches of the external carotid artery and the fronto-orbital terminal branches of the ophthalmic artery (supratrochlear artery). Furthermore, in cases of high-grade stenoses or occlusions, it is particularly important to investigate the flow direction and velocity in the precommunicating segment of the anterior cerebral artery (A1 segment), proving cross flow, and the flow velocities in the P1 segment of the posterior cerebral artery, indicating collateral flow through the posterior communicating artery.

The assessment of the collateral systems requires transcranial Doppler (TCD). The inclusion of the collaterals in the classification of stenosis has the advantage of a clear identification of hemodynamically relevant and thus high-grade stenoses (≥70% NASCET). Established collateral flow is the most powerful criterion, excluding a less than severe stenosis irrespective of the intrastenotic PSV. There is a clear sonographic evidence of collaterals in severe stenosis or occlusion [29].

The multiparametric approach – Additional (secondary) criteria

Criterion 6 - Prestenotic diastolic flow deceleration of the CCA

Typically in severe ICA stenoses (≥ 70% NASCET) there is a distinct prestenotic diastolic flow deceleration of the...
common carotid artery (CCA) due to the increased flow resistance (Figure 13). This increased flow resistance is the consequence of the following distinct obstructive vessel disease in the ICA.

**Criterion 7 - Poststenotic flow disturbances**

Typically in severe stenoses (≥70% NASCET) there are pronounced poststenotic separation effects due to transition from laminar to turbulent flow (“steps in the gravel”).

If measurement of PSV is not possible in the area of greatest narrowing of the lumen, thus, criterion 7 is important.

Evidence of a severe stenosis: behind the extended acoustic shadow (Figure 14) aliasing and flow disturbances are visible in color coded imaging. For a high reliability aliasing and flow disturbances prove a high grade stenosis in the vessel segment not visible due to the extent acoustic shadow.

**Criterion 8 - End-diastolic flow velocity in the area of greatest narrowing of the lumen**

In severe stenosis (≥70% NASCET) end-diastolic flow velocities more than 100 cm/s are to be expected. Criterion 8 is important if intrastenotic PSV can not be measured sufficiently.

**Criterion 9 - Confetti sign**

The so-called confetti sign is the consequence of perivascular tissue vibrations. The confetti sign is generated by vibration of perivascular soft tissue due to an impingement of a highly accelerated jet flow.

The finding is distal to severe stenoses (≥70% NASCET) with a typical delta-shaped configuration (Figure 15).

**Criterion 10 - Index of stenosis / carotid velocity ratio**

ICA/CCA – “carotid ratio” (ratio of PSV of the ICA and CCA)

\[
\text{Index} = \frac{PSV_{ICA}}{PSV_{CCA}}
\]

The carotid ratio is important for example for the identification of a tandem stenosis or an ICA hyperperfusion.

Table 2 provides a summary of all main/primary criteria and additional/secondary criteria for stenoses graded 10% to occlusion according to NACEST.
Ultrasonography of carotid stenosis

Figure 14. Measurement of PSV is not possible in the area of greatest narrowing due to an extended acoustic shadow (upper part). Behind this extent acoustic shadow aliasing and flow disturbances are visible in color coded imaging (lower part).

Figure 15. Confetti sign distal to a severe ICA stenosis with the typical delta-shaped configuration [32].

Table 2. Summary of all main/primary (Crit. No. 1-5) and additional/secondary (Crit. No. 6-10) criteria for stenoses graded 10% to occlusion according to NACEST. Grading of the stenoses occur in steps of 10%. The PSV values of criterion 3 are taken from Figure 2.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>10-40%</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
<th>90%</th>
<th>Occlusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 B-mode: verification of stenosis</td>
<td>+++</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>2 Color coded imaging of flow: local flow acceleration (aliasing)</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
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<td>&gt;50 normal</td>
<td>&gt;50 normal</td>
<td>&gt;50 reduced</td>
<td>&lt;50 reduced</td>
<td>&lt;30 strongly reduced</td>
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<td>(+)</td>
<td>++</td>
<td>+++</td>
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<td>7 Poststenotic flow disturbances</td>
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<td>+</td>
<td>+</td>
<td>++</td>
<td>+++</td>
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<tr>
<td>8 Stenotic end-diastolic flow velocity (EDV) (cm/s)</td>
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<td>&lt;100</td>
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<td>(+)</td>
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(+) can exist + exist ++ regular present +++ very pronounced present
Diagnostic ultrasound has the potential to classify and grade carotid disease with high reliability, taking into account morphological and complex hemodynamic parameters.

Abbreviations


Competing interests

The authors declare no conflict of interest.

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