B-Mode Flow Imaging of the Carotid Artery
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Background and Purpose—B-mode ultrasonography has been used to evaluate cervical carotid artery lesions. Recently, the technology for direct visualization of blood reflectors has made B-mode flow imaging (B-flow) possible without the limitations of Doppler technology. We evaluated the efficacy of B-flow in examining the cervical carotid artery.

Methods—Sixty patients with ischemic cerebrovascular disease were examined. Conventional B-mode imaging and blood flow images by power Doppler imaging (PDI) and B-flow were obtained.

Results—B-flow enabled simultaneous imaging of tissue and blood flow. Compared with PDI, B-flow provided higher spatial resolution and higher frame rate hemodynamic imaging. Consequently, a clear definition of the vessel lumen was obtained even in the stenotic portion of the carotid artery. In evaluating the degree of carotid stenosis, B-flow measurement agreed with digital subtraction angiography as well as PDI measurement. In addition, bloodstream swirl at the site of wall ulceration or vascular elongation was observed.

Conclusions—B-flow was prominent in visualizing hemodynamic flow and detection of stenotic lesion in the cervical carotid artery. Combined with conventional B-mode technique, B-flow seems to be useful in evaluating carotid stenosis.

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Key Words: carotid arteries ■ carotid stenosis ■ diagnostic imaging ■ ultrasonography

B-mode ultrasonography has been widely used to examine the carotid artery. This method provides not only real-time information about both the lumen and vessel wall but also microscopic characteristics of carotid lesion. In addition, the technology of color Doppler flow imaging (CDFI) enabled display of the velocity and flow direction of red blood cells as well as vascular structures. Furthermore, the introduction of power Doppler imaging (PDI) provided homogeneous color signals and generated angiography-like visualization of the vascular lumen surface. Consequently, CDFI and PDI have made measurement of the residual lumen of carotid stenosis more reliable than with conventional B-mode imaging.

Recently, a new method for the detection of blood flow by ultrasound (B-flow) has been developed. With this technology, direct visualization of blood reflectors has made B-mode flow imaging possible without the limitations of Doppler technology such as aliasing, signal dropout at orthogonal detection angles, and wall filter limitations. B-flow visualizes real-time hemodynamic flow in relation to stationary tissue. We evaluated the efficacy of B-flow in examining the cervical carotid artery in patients with ischemic cerebrovascular disease.

Subjects and Methods
Sixty patients (50 men and 10 women; age range, 35 to 84 years) with ischemic cerebrovascular disease were included in this study. Sixteen patients had experienced symptomatic cerebral infarction, 24 patients showed asymptomatic cerebral infarction on MRI, 7 patients were seen for preoperative evaluation of carotid stenosis prior to carotid endarterectomy, and 13 patients were seen for follow-up studies after carotid endarterectomy.

Cervical carotid arteries were examined in all patients using LOGIC 700 ultrasound device (GE Medical Systems) with a 6.5-MHz probe focusing on the level around the carotid bifurcation. Routine B-mode and blood flow images by PDI and B-flow were obtained. Sequential parallel longitudinal views of flow were displayed. We closely watched vessel walls and hemodynamic flow simultaneously. We calculated the degree of stenosis by measurements of luminal diameters contrasted by power Doppler color signals or B-flow signals.

Selective digital subtraction angiography (DSA) of the carotid artery was performed in 15 patients who were suspected of having carotid stenosis on ultrasonography. The degree of carotid stenosis was derived from the minimum internal carotid and the common carotid luminal diameters, because the common carotid artery is more easily visualized in ultrasonography. Simple regression analysis was used for statistical evaluation of the correlation between measurements of stenosis by sonographic and angiographic methods.

Results
B-flow enabled simultaneous imaging of tissue and real-time blood flow in all patients. Flow pattern was shown in gray-scale imaging. Compared with PDI, B-flow provided higher spatial resolution and higher frame rate hemodynamic imaging without information on velocity and direction. Consequently, clear definition of the vessel lumen without overlay was obtained (Figure 1). However, resolution of vessel wall tissue was inferior to that of the conventional B-mode and PDI methods.

B-flow provided clearer definition of the vessel lumen even in the carotid stenosis (Figure 2). PDI tended to
overestimate the normal vessel lumen and underestimate the vessel lumen of the severely stenotic portion.

Fifteen patients were suspected of having carotid stenosis and underwent DSA. Measurement of the percentage of stenosis in both sonographic techniques (B-flow and PDI) and DSA correlated significantly ($P<0.0001$; Figure 3). However, the coefficient of correlation was higher for DSA versus B-flow ($r=0.977$) than for DSA versus PDI ($r=0.954$). Compared with B-flow, PDI has a tendency to underestimate the percentage of stenosis in severely stenotic lesions and overestimate the percentage of stenosis in mildly stenotic lesion.

Bloodstream swirl was clearly observed at the site of wall ulceration (Figure 4) or vascular tortuosity (Figure 5) on B-flow in 6 patients with symptomatic or asymptomatic cerebral infarction. Such complex hemodynamics seems to relate to the formation of thrombus and the occurrence of stroke.

**Discussion**

B-mode ultrasonography has been used for real-time noninvasive assessment of the carotid artery. This method provides...
precise information about lumen and vessel wall characteristics.\textsuperscript{1,2} Subsequent introduction of CDFI and PDI enabled visualization of blood flow. In particular, homogeneous color signals by PDI provides angiography-like visualization of the vascular lumen surface and has been used to approximate the degree of carotid stenosis.\textsuperscript{5} The intensity of color signals on PDI essentially depends on the reflected echo amplitude from red blood cells, thus indicating the density of blood cells within the sample volume.\textsuperscript{5}

B-flow technology was achieved by General Electric’s digitally encoded ultrasound. Coded sound waves are transmitted into the body and vasculature, and the returning signals are then decoded and displayed, as in B-mode. This technology enables boosting of weak flow refector signals from blood reflectors and suppresses unwanted signals and frequencies from tissue. Consequently, B-flow can visualize real-time hemodynamic flow in relation to stationary tissue. In fact, B-flow provided higher spatial resolution for demonstrations of vessel anatomy and higher frame rate hemodynamic imaging than PDI.

In evaluating the degree of carotid stenosis, B-flow measurement agreed with DSA as well as PDI measurement. Both methods obtained much better correlation from longitudinal views than results shown in other studies.\textsuperscript{3–5} Although this good correlation may be influenced by the small sample bias, we feel it is mainly due to meticulous examination. In addition, the coefficient of correlation was slightly higher for DSA versus B-flow than for DSA versus PDI. This result is due to clearer definition of the vessel lumen without the overwriting seen with B-flow. In fact, the B-flow hemodynamic image resembles that of angiography. In PDI, overestimation of the normal vessel lumen is caused by overwriting, and underestimation of the stenotic vessel lumen is caused by limitations in detecting flow. Consequently, PDI underestimated the percentage of stenosis in severely stenotic lesions and overestimated the percentage of stenosis in mildly stenotic lesions.

It must be emphasized that B-flow provides a detailed hemodynamic image of phenomena such as bloodstream swirl. Visualization of such a complex flow pattern has not been achieved by CDFI or PDI. Thrombus formed by atherosclerosis is important in considering a cause of cerebral infarction. In addition, B-flow visualized bloodstream swirl at the site of wall ulceration or vascular tortuousness. This complex flow pattern might be related to shear stress–induced platelet aggregation and become another cause of thrombus formation in stroke patients.\textsuperscript{10} Careful analysis of flow patterns at the carotid bifurcation in relation to the pathogenesis of ischemic cerebrovascular disease will be the subject of further study.

In conclusion, B-flow is highly effective in visualizing hemodynamic flow and in detecting stenotic lesions in the cervical carotid artery. Combined with conventional B-mode technique, B-flow seems to be useful in evaluating carotid stenosis, especially in patients with ischemic cerebrovascular disease.

References
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