

COMPARISON OF THREE DIFFERENT ULTRASOUND TECHNIQUES FOR BLOOD FLOW VOLUME MEASUREMENTS IN THE EXTRACRANIAL CAROTID SYSTEM

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Purpose: Non-invasive measurement of cerebral blood flow volume can be helpful in the prevention, diagnosis, and follow-up of cerebrovascular diseases. This study aimed to compare the accuracy levels of blood flow volume estimations in the bilateral common carotid, internal carotid and external arteries of healthy volunteers obtained with color Doppler, power Doppler and B-flow US with the use of an internal standard.

Methods: Blood flow volumes of the bilateral common carotid, internal carotid and external carotid arteries of 40 healthy volunteers (17 men, 23 women, age range 27-44 years, mean age 34.43 ± 8.45) were measured using color Doppler, power Doppler and B-flow US. The total of blood flow volume estimates in the internal and external carotid arteries was compared with the ipsilateral common carotid artery flow. Considering that no difference would be demonstrated with an accurate technique, the difference (percentage inconsistency) was accepted as a measure of the accuracy of the method, and three US techniques were compared.

Results: Percentage inconsistency (mean \pm SD) was $19.21 \pm 15.51\%$ for color Doppler, $13.45 \pm 11.02\%$ for power Doppler, and $4.03 \pm 4.01\%$ for B flow US. B flow sonography provided a better correlation of the common carotid artery blood flow volume with the sum of internal and external carotid artery blood flow, compared to the other Doppler methods. For the measurement of carotid blood flow volume, the differences in inconsistency between B-flow and color Doppler, as well as B-flow and power Doppler were statistically significant ($p < 0.01$).

Conclusion: B-flow imaging provides more accurate measurements for blood flow volume estimations in the carotid artery, compared to other sonographic methods. B-flow US can be helpful for noninvasive estimation of cerebrovascular blood flow volume.

Key Words: Cerebral Blood Flow, Cerebrovascular Diseases, Color Doppler Ultrasonography, Power Doppler Ultrasonography, B-Flow Ultrasonography.

EKSTRAKRANİAL KAROTİD SİSTEMDE KAN AKIM HACİMİ ÖLÇÜMLERİNDE ÜÇ FARKLI US TEKNİĞİNİN KARŞILAŞTIRILMASI

Amaç: Serebral kan akım hacminin non-invaziv ölçümü, serebrovasküler hastalıkların önlenmesi, tanısı ve takibinde yardımcı olabilir. Bu çalışmada, sağlıklı gönüllülerde bilateral ana karotid, internal karotid ve eksternal karotid arterlerden renkli Doppler, power Doppler, ve B-flow ultrasonografi ile elde edilen kan akım hacim ölçümleri doğruluk derecelerinin, bir internal standard kullanılarak karşılaştırılmasını amaçladık.

Gereç ve Yöntem: Kırk sağlıklı gönüllüde (17 erkek, 23 kadın, yaş aralığı 27-44, ortalama yaş 34.43 ± 8.45) bilateral ana karotid, internal karotid ve eksternal karotid arterlerde kan akım hacimleri renkli Doppler, power Doppler ve B-flow sonografi kullanılarak ölçüldü. Internal ve eksternal karotid arterlerde kan akım hacim ölçümleri toplamı, ipsilateral ana karotid arter akımı ile karşılaştırıldı. Doğru bir tekniğin hacim ölçümleri arasında fark bulunmayacağı düşünüldü. Ölçümler arasındaki farklılık (uyumsuzluk yüzdesi) yöntemin doğruluğunun ölçütü olarak kabul edildi ve üç ultrasonografi tekniği karşılaştırıldı.

Bulgular: Uyumsuzluk yüzdesi (ortalama \pm SD), renkli Doppler için 19.21 ± 15.51 , power Doppler için 13.45 ± 11.02 , ve B-flow ultrasonografi için 4.03 ± 4.01 olarak bulundu. B-flow ultrasonografi, diğer Doppler yöntemleri ile karşılaştırıldığında, ana karotid arter kan akım hacmi ile, internal ve eksternal karotid arterler kan akımı toplamları arasında daha iyi bir korelasyon sağladı ($p < 0.01$).

Sonuç: B-flow görüntüleme, diğer sonografik yöntemlere göre, karotid arterlerde daha doğru kan akım hacim ölçümleri yapılabilmesini sağlar. Serebrovasküler kan akım hacminin non-invaziv tahmini için B-flow sonografi yararlı bir yöntem olabilir.

Anahtar Kelimeler: Serebral Kan Akımı, Serebrovasküler Hastalıklar, Renkli Doppler Ultrasonografi, Power Doppler Ultrasonografi B, Flow Ultrasonografi.

INTRODUCTION

The quantitative measurement of cerebral blood flow volume (BFV) is clinically useful in a variety of cerebrovascular conditions. Total cerebral BFV can be assessed by measuring flow in the vessel supplying the brain. Hence, quantification of carotid blood flow can be considered an important neuromonitoring tool. An accurate BFV measurement technique is especially of great value in conditions such as monitoring cerebral BFV before and after carotid endarterectomy, hemodynamic evaluation of a carotid stenosis, the presence of collateral pathways, and estimation of the shunt volume in cerebral arteriovenous malformations (1-4). Furthermore, sonographic assessment of the cerebral BFV may be an additional parameter that might increase the diagnostic sensitivity of US in stroke patients, and may have prognostic relevance (5).

In daily clinical practice, Doppler US is a noninvasive technique used for measuring blood flow in the vessels supplying the brain. With Doppler imaging, the artery to be examined can be well delineated and chosen for interrogation. However, spectral Doppler imaging tends to significantly overestimate cerebral BFV due to some inherent limiting features (6). For this reason, sonographic planimetric measurement methods are used to complement duplex Doppler scanning, one of them being power Doppler imaging. B-flow imaging, on the other hand, is a recently introduced non-Doppler technology enabling real-time imaging of the flowing blood, which may be a promising technique for quantification of blood flow volume.

This study aimed to compare the accuracy levels of blood flow volume estimations in the bilateral common carotid (CCA), internal carotid (ICA), and external carotid arteries (ECA) of healthy volunteers obtained with color Doppler, power Doppler and B-flow US. For this purpose, in vivo internal validation was performed to determine the carotid BFV in a group of healthy subjects.

MATERIALS AND METHODS

Blood flow volumes of the bilateral common carotid, internal carotid and external carotid arteries of 40 healthy volunteers were measured using color Doppler, power Doppler and B-flow US. Of the subjects, 23 were women and 17 were men. The mean patient age was 34.43 ± 8.45 years (mean \pm SD), with an age range of 27-44 years. None of the subjects had a known history of any cardiovascular disease, diabetes mellitus, or smoking.

Sonograms were obtained with a GE Logiq 9 (MI, USA) using a 4-10 MHz linear transducer. After the explanation of the study protocol, all volunteers gave informed consent before blood flow volume measurements.

We assumed that in an ideal flow volume measurement technique the sum of the blood flow volume of ICA and ECA would be equal to that of CCA. Any difference between them would indicate the inconsistency of the imaging technique applied.

Intravascular flow volumes were calculated within the ICA, ECA and CCA using color Doppler, power Doppler and B-flow US. Volunteers were allowed to rest on the examination table for 10 minutes before volume measurements were obtained with sonography. All blood vessels (ICA, ECA, and CCA) of 80 groups of the extracranial carotid system were examined by these three sonographic methods in all of the subjects.

A routine examination of the carotid arteries was performed before volume flow measurements, in order to exclude any pathologic processes like atherosclerosis or stenosis. The subjects were examined with color Doppler US (CDUS) first, followed by power Doppler US (PDUS) and B flow imaging. For flow volume measurements a straight segment of the vessels (ECA, ICA and CCA) at least 2 cm from the bifurcation was selected. The same sagittal plane was used for the flow measurements, maintaining the plane of the section as constant as possible. Windows of color Doppler, power Doppler and B-flow images were used to place the sample volume for supplemental PW interrogation at the selected site of measurement. A large Doppler sample volume corresponding to the vessel diameter was used. The angle of insonation was adjusted to 60 degrees or below and was kept constant while alternating between different modes. For color and power Doppler US, the imaging parameters like color gain or wall filter were adjusted for each image with optimal color saturation with no aliasing or color "bleeding" over the lumen. High sensitivity levels were used for B-flow ultrasound with a single focus positioned just below the range of interest.

The luminal diameter of each vessel, which was determined as the distance between the parallel walls of the vessel contrasted by color Doppler, power Doppler or B-flow signals, was measured on the magnified images of the vessel under study. The diameter of the vessel was measured as close to the line of interrogation as possible, for better accuracy. The intravascular blood flow volume measurements were automatically calculated by the built-in software of the ultrasound device, as the product of angle-corrected time-averaged flow velocity and the cross-sectional area of the vessel. The flow

measurements were repeated three times for each vessel and for each US technique and then averaged to provide the blood flow volume estimates of each vessel in order to minimize the random errors to an acceptable level. All sonographic examinations were performed by a single radiologist experienced in sonography.

For each US method, the sum of ICA and ECA blood flow volumes was compared with that of the ipsilateral CCA. The percent difference between the sum of ICA and ECA blood flow volume estimates and that of the CCA was assumed to express the inconsistency of a method. This difference was calculated by subtracting the total ICA and ECA blood flow from the CCA flow. The absolute difference was divided by the CCA flow and expressed as a percentage. Statistical analysis was performed with commercially available statistical software (SPSS 11.0, Statistical Package for the Social Sciences, Chicago, IL, USA). To compare the percentage inconsistency of the two techniques, a paired t test was used. The level of significance was taken at $p < 0.01$. Kendall's W test was used for interobserver variability and the significance level was set at $p < 0.01$.

RESULTS

The overall results of flow volume measurements of 80 groups of ICA, ECA and CCA obtained by color Doppler, power Doppler and B-flow US techniques are summarized in Table 1. With all the techniques, the blood flow estimates were consistently greater for CCA than for the sum of its branches. The percent inconsistency values (\pm SD) were $19.21 \pm 15.51\%$, $13.45 \pm 11.02\%$, and $4.03 \pm 4.01\%$ for CDUS, PDUS and B-flow US, respectively. The lowest inconsistency level was obtained with B-flow US, which was significantly different from the levels of both CDUS and PDUS in pairwise comparisons ($p < 0.001$), indicating that with B-flow imaging a more accurate estimate of blood flow volume can be obtained. The inconsistency level of CDUS was greater than that of PDUS, but this difference was not statistically significant ($p = 0.027$).

The highest flow volume values in the vessels were obtained with PDUS, followed by quantifications obtained by CDUS and B-flow imaging. For all the US techniques there was a significant difference in the BFV measurements between CCA and its branches (ICA + ECA) ($p < 0.001$). However,

Table 1. Blood flow volume (BFV) measurements (*) CCA, ICA and ECA obtained with CDUS, PDUS and B-flow imaging.

	CDUS (ml/min)	PDUS (ml/min)	B-flow (ml/min)
CCA	448.34 \pm 119.73	457.56 \pm 136.32	354.67 \pm 110.34
ICA	249.31 \pm 92.23	266.12 \pm 91.67	241.45 \pm 69.24
ECA	143.98 \pm 68.49	149.98 \pm 69.25	120.65 \pm 61.87

*mean \pm SD, ml/min

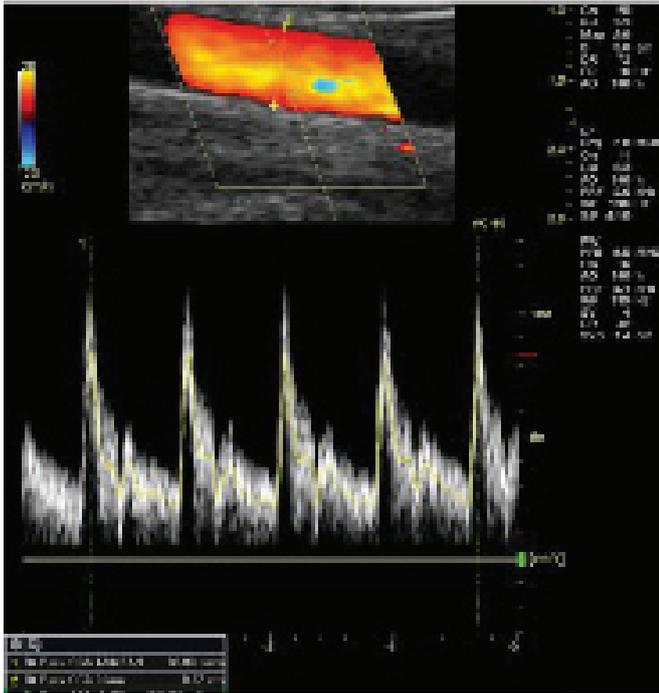


Figure 1a: Blood flow volume measurements of CCA obtained with color Doppler US, in a 28-year-old healthy subject. For flow volume measurements a straight segment of the vessel was selected and a large Doppler sample volume corresponding to the vessel diameter was used at the level of interrogation (BFV = 560.73 ml/min).

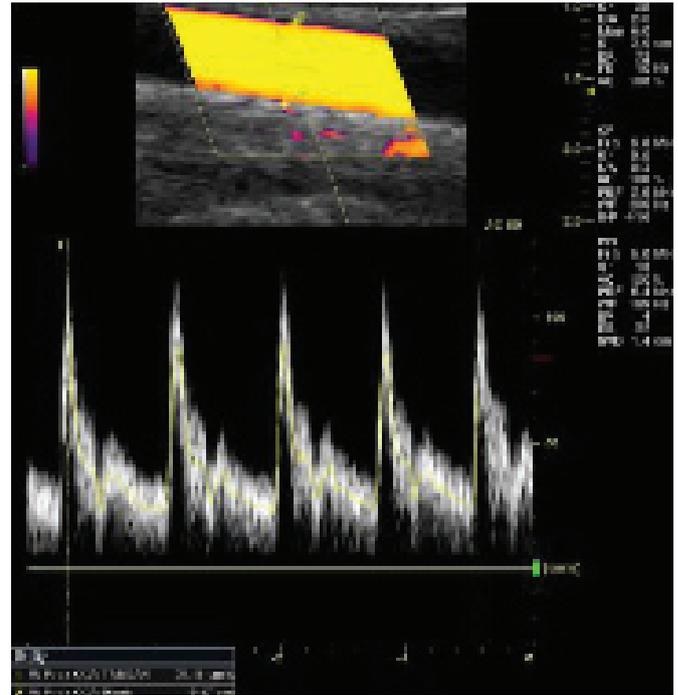


Figure 1b: In the same subject the blood flow volume measurements obtained with power Doppler US at the same level are shown (BFV = 593.01 ml/min).

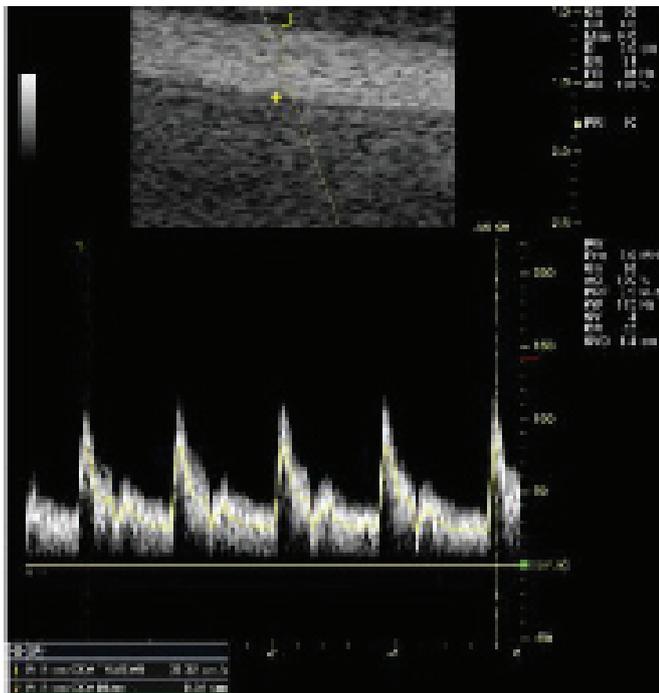


Figure 1c: Note that blood flow volume calculations obtained at the same level of CCA using B-flow imaging reveals a lower value (BFV = 485.41 ml/min) compared to color or power Doppler US.

there was better correlation between the CCA BFV and the sum of (ICA and ECA) BFV by the B-flow technique than with the either CDUS or PDUS (Figures 1). When B-flow imaging was used, the sum of ICA and ECA flow volumes

gave the closest values to the CCA flow volume estimate of the ipsilateral artery. The intraobserver variability was 0.819, which was insignificant and within acceptable levels.

DISCUSSION

Accurate quantification of cerebral BFV has many potential applications in vascular medicine, neurology and neurosurgery. Cerebral blood flow can be assessed based on information on flow in capillaries or by measuring flow in the vessel supplying the brain. The quantitative measurement of cerebral BFV is achieved by various methods such as stable Xenon CT, single-photon emission CT, positron emission tomography, and perfusion magnetic resonance. However, these techniques have some limitations such as ionizing radiation, invasiveness, or high cost. Moreover, they require the transfer of patients to the imaging or radionuclear facility, which is another main disadvantage, especially for debilitated, sedated or ventilated patients (7-9). Color Doppler US, on the other hand, can be instituted for the measurement of blood flow volume, without the disadvantages of the mentioned techniques (9). However, CDUS has also some important and limiting inherent features in the visualization of dynamic pulsatile flow, like decreased spatial resolution and frame rate, or high angle dependency. The vessel diameter measurements from a color Doppler image may be erroneous as the resolution of these systems is poor and the spread of color overlay leads to artifactual increases in the apparent diameter (10-12).

For flow quantification, some sonographic planimetric measurement methods are used to complement duplex Doppler scanning, in an attempt to eliminate some of the disadvantages

of CDUS. Power Doppler imaging is the most widely used of these. PDUS uses a color map that displays the integrated power of the Doppler signal instead of its mean frequency shift (13). The advantages of PDUS include a higher sensitivity to slow flow, the absence of aliasing and independence of the angle. It is also suggested that, because of its superior sensitivity, the measurement of the vessel diameter with PDUS is more accurate. The main disadvantages of PDUS include the presence of more flash artifacts compared to CDUS because of higher sensitivity to movement and inability to detect flow direction (14-16). In both color and power Doppler US, the flow is presented as an overlay to the B-mode image. As a result, any tissue motion may be registered as a color flash artifact, which may obscure true flow data. Maximizing the color fill-in of vessels with low pulse repetition frequency, low wall filter, and high color gain settings will result in some overwriting of the vessel wall, which can prevent accurate estimation of the inner luminal diameter, measured between intimal layers (12).

B-flow imaging is a recently introduced flow technology that extends B-mode imaging capabilities to blood flow, including high frame rate and high spatial, temporal, and contrast resolution (12, 17, 18). It enables real-time imaging of particulate constituents within the flowing blood in a gray-scale presentation, while simultaneously depicting surrounding anatomy, but without the need for overlays. This explains the unobstructed view of the vessel lumen obtained by the B-flow technique. B-flow images are generated by using digitally encoded US technology consisting of a transmit encoder and a receive decoder in a digital beam former. The digitally encoded sound waves are transmitted through soft tissues, and vessels. The returning signals are then decoded and displayed. In stationary tissue the echoes remains the same, but in regions of moving blood there is a change from one pulse to the next. Basically, in B-flow imaging, the echoes are subtracted from one another and the difference is amplified to provide the display of movement. Blood flow usually cannot be seen in traditional B-mode sonography, since weak echoes from blood cells are partially degraded due to reverberation and other artifacts. On the other hand, in B-flow sonography, which is actually a gray-scale imaging method, signals from blood reflectors are enhanced while the tissue return signal is suppressed, without the limitations of CDUS or PDUS. In B-flow imaging, a better frame rate and axial resolution than in color flow imaging is obtained because of fewer pulses applied along each line and the use of high frequency wideband pulses. B-flow provides an unobstructed view of the vessel lumen depicting the blood echoes in a gray-scale presentation simultaneously with tissue morphology, unlike color Doppler flow in which the color signals are superimposed onto gray-scale images. The presence of fewer imaging parameters that are easier to optimize, and angle independency are further advantages of B-flow imaging. It may also be more reliable in the evaluation of small or tortuous vessels than other sonographic modalities, as the flow phenomena are less angle dependent and better demarcated against the vessel walls with simultaneous detection of flow (12, 17, 19, 20).

In duplex scanning measurements of blood flow volume vessel diameter or surface area are combined with Doppler-derived velocity determinations to obtain estimates of volume flow (21, 22). However, this technique is subject to some errors. These errors of volume flow measurement arise from inaccurate estimation of blood velocity and diameter measurement by off-axis sampling (due to respiratory movement of the carotid arteries or pulsatile vessels), tortuous vessels, turbulent or non-axial flow, artifactual color signals, poor color setting, variations of vessel diameter during cardiac cycle and respiratory vessel movement (6, 23). The blood flow volume is calculated with the following equation: Blood Flow Volume = mean velocity x vessel cross-sectional area = mean velocity x $\pi/4$ x (vessel diameter)². The cross-sectional area of the vessel is usually calculated from a static vessel diameter measured at the location of the Doppler sample volume, which assumes a circular vessel configuration. On the basis of this equation, any minor error in the vessel diameter measurement may dramatically alter the estimated flow volume. Overlay of the intimal layer by color coding may cause overestimation of the vessel diameter, which is a critical parameter blood flow volume calculation, as the volume formula suggested (24).

In our study, we compared the accuracy levels of blood flow volume estimations in the bilateral CCA, ICA, and ECA of healthy volunteers obtained with color Doppler, power Doppler and B-flow US by the use of an internal standard. The results showed that for all the US techniques there was a significant difference in the BFV measurements between CCA and the sum of its branches, which may be regarded as supportive evidence for the inaccuracy of these sonographic techniques. With all the techniques, the blood flow estimates were consistently greater for CCA than for the sum of its branches. However, there was a better correlation between the BFV and the B-flow technique than either the CDUS or PDUS techniques.

Potential sources of error in BFV estimations such as turbulent flow or off-axis sampling seem to be common to all sonographic techniques (23). We assume that diameter measurement is estimated better with B-flow imaging, which is probably one of the major contributions to its greater accuracy for blood flow volume estimations. This accuracy of B-flow imaging in diameter measurement may be due to the elimination of sonographic artifacts such as color overwriting, aliasing and blooming, providing better visualization of the lumen (12, 17).

B-flow imaging has some shortcomings, despite the mentioned advantages. A major limitation of this technique is that excessive pulsation of the vessel leads to movement of the surrounding structures and this may blur the exact margins of the vessel wall. Further disadvantages include decreased sensitivity with increased depth, difficulty demonstrating slow flow, and background flash artifacts (18). Some disadvantages of traditional ultrasound such as operator dependency or inability to obtain signals deep in a calcified structure also apply to B-flow imaging.

In conclusion, B-flow imaging is a more accurate volume quantification method compared to color or power Doppler imaging. Therefore, it seems to be more reliable also for the estimation of global cerebral BFV assessed by measurement of blood flow volumes of the extracranial arteries. Even though sonographic methods have been shown to overestimate flow volume measurement, B-flow imaging, which has higher accuracy levels, has potential use in cerebrovascular diseases mainly because of its low operational cost and bedside applicability for the monitorization of critically ill patients. However, this method needs further validation with larger series with cerebrovascular disease.

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1. Uematsu S, Yang A, Preziosi TJ, Kouba R, Toung TJ. Measurement of carotid blood flow in man and its clinical application. *Stroke* 1983; 14: 256-266.
2. Dalla Costa F, Signorini GP, Previato Schiesari A. Quantitative evaluation of carotid blood flow before and after surgery. *Int Angiol* 1987; 6: 371-373.
3. Wada T, Kodaira K, Fujishiro K, Okamura T. Correlation of common carotid flow volume measured by ultrasonic quantitative flowmeter with pathological findings. *Stroke* 1991; 33: 319-323.
4. Seidel E, Eicke BM, Tettenborn B, Krummenauer F. Reference values for vertebral artery flow volume by duplex sonography in young and elderly adults. *Stroke* 1999; 30: 2692-2696.
5. Ruprecht-Drfler P, Brechtelsbauer D, Schließer M, Puls I, Becker G. Prognostic and diagnostic value of global cerebral blood flow volume and cerebral transit time in acute stroke. *Ultrasound in Med Biol* 2002; 28: 1405-1411.
6. Eicke BM, Tegeler CH. Ultrasonic quantification of blood flow volume. In Tegeler CH, Babikian VL, Gomez CR, eds. *Neurosonology*. New York, NY: Mosby-Year Book; 1996: 101-110.
7. Ho SS, Chan YL, Yeung DK, Metreweli C. Blood flow volume quantification of cerebral ischemia: comparison of three noninvasive imaging techniques of carotid and vertebral arteries. *AJR Am J Roentgenol* 2002; 178: 551-556.
8. Soustiel JF, Glenn TC, Vespa P, Rinsky B, Hanuscin C, Martin NA. Assessment of cerebral blood flow by means of blood-flow-volume measurement in the internal carotid artery: comparative study with a 133xenon clearance technique. *Stroke* 2003; 34: 1876-1880.
9. Spilt A, Box FM, van der Geest RJ, Reiber JH, Kunz P, Kamper AM, Blauw GJ, van Buchem MA. Reproducibility of total cerebral blood flow measurements using phase contrast magnetic resonance imaging. *J Magn Reson Imaging* 2002; 16: 1-5.
10. Kremkau FW. Doppler Instruments. In: *Diagnostic Ultrasound: Principles and Instruments*, 4th ed. Philadelphia, Pa: WB Saunders; 1993: 211-214.
11. Cosgrove D, Meire H, Dewbury K. Doppler. In: *Abdominal and General Ultrasound*, Vol. 1. 1st ed. Edinburgh, Churchill Livingstone; 1993: 92.
12. GE Ultrasound Europe. B-Flow: a new way of visualizing blood flow-ultrasound technology update. Solingen, Germany: GE Ultrasound Europe, 1999.
13. Rumack CM, Wilson SR, Charboneau JW. Physics of Ultrasound. In: *Diagnostic Ultrasound*, Vol. 1, 2nd ed. Missouri, Mosby-Year Book; 1998: 26.
14. Konje JC, Abrams K, Bell S, de Chazal RC, Taylor DJ. The application of color power angiography to the longitudinal quantification of blood flow volume in the fetal middle cerebral arteries, ascending aorta, descending aorta, and renal arteries during gestation. *Am Obstet Gynecol* 2000; 182: 393-400.
15. Griewing B, Morgenstern C, Driesner F, Kallwellis G, Walker ML, Kessler C. Cerebrovascular disease assessed by color-flow and power Doppler ultrasonography. Comparison with digital subtraction angiography in internal carotid artery stenosis. *Stroke* 1996; 27: 95-100.
16. Steinke W, Meairs S, Ries S, Hennerici M. Sonographic assessment of carotid artery stenosis: Comparison of power Doppler imaging and color Doppler flow imaging. *Stroke* 1996; 27: 91-94.
17. Bucek RA, Reiter M, Koppensteiner I, Ahmadi R, Minar E, Lammer J. B-Flow evaluation of carotid arterial stenosis: Initial experience. *Radiology* 2002; 225: 295-299.
18. Weskott HP. B-Flow: a new method for the detection of blood flow. *Ultraschall Med* 2000; 21: 59-65.
19. Tola M, Yurdakul M, Cumhuri T. Combined use of color duplex ultrasonography and B-flow imaging for evaluation of patients with carotid artery stenosis. *Am J Neuroradiol* 2004; 25: 1856-1860.
20. Umemura A, Yamada K. B-mode flow imaging of the carotid artery. *Stroke* 2001; 32: 2055-2057.
21. Gill RW. Measurement of blood flow by ultrasound: accuracy and sources of error. *Ultrasound Med Biol* 1985; 11: 611-625.
22. Oates CP, Williams ED, McHugh MI. The use of Dasonics DRF400 duplex ultrasound scanner to measure volume flow in arteriovenous fistulae in patients undergoing hemodialysis: an analysis of measurement uncertainties. *Ultrasound Med Biol* 1990; 16: 571-579.
23. Ho SSY, Metreweli C. Preferred technique for blood volume measurement in cerebrovascular disease. *Stroke* 2000; 31: 1342-1345.
24. Burns PN. The physical principles of Doppler and spectral analysis. *J Clin Ultrasound*. 1987; 15: 567-590.