Clinical Studies

Doppler Vibrometry: Assessment of Arterial Stenosis By Using Perivascular Tissue Vibrations without Lumen Visualization

Siddhartha Sikdar, PhD, Sandeep Vaidya, MD, Manjiri Dighe, MD, Orpheus Kolokythas, MD, Jae Hwan Kim, BS, Kirk W. Beach, MD, PhD, and Yongmin Kim, PhD

PURPOSE: To correlate vibration frequency and duration at Doppler vibrometry with stenosis severity determined at catheter angiography.

MATERIALS AND METHODS: Sixteen patients (eight women) scheduled to undergo abdominal or pelvic angiography were recruited after providing informed consent. An ultrasonography (US) scanner was customized to acquire raw echo data before conventional Doppler processing. Data were acquired from perivascular tissue regions proximal to stenoses, close to the most narrow lumen, and distal to stenoses in the renal, hepatic, common iliac, and superior mesenteric arteries. The data were processed to quantify vibration frequency and duration. The minimum lumen diameter and the pre- and poststenotic lumen diameters were quantified from angiograms. One patient with a hepatic artery stenosis did not yield measurable vibrometry data due to significant bowel gas.

RESULTS: Stenoses (diameter reduction, 43%–91%) were angiographically measured in the six renal arteries, four hepatic arteries, three iliac arteries, and one superior mesenteric artery yielding vibrometry data. Three iliac arteries were normal (\(<30\%\) diameter reduction at angiography). For these 17 arteries, the vibration frequency was higher with a greater percentage of stenosis \(r = 0.75; P < 0.001\) and a smaller minimum lumen diameter \(r = 0.72; P < 0.001\). The vibration duration increased with a greater percentage of stenosis \(r = 0.7; P < 0.001\).

CONCLUSIONS: Preliminary results indicate that the vibration frequency and duration can be used to quantitatively estimate stenosis severity. Doppler vibrometry is complementary to duplex US and does not require lumen visualization.

J Vasc Interv Radiol 2009; xx:xxx

DUPLEX ultrasonography (US) is the diagnostic method of choice for the initial assessment of abdominal and pelvic artery stenoses (1). The duplex examination can be technically challenging and is often time-consuming owing to the need to visualize the artery lumen and stenosis site. Although the negative predictive value of the duplex examination is typically high, positive findings often need further confirmation with use of conventional angiography, magnetic resonance angiography, or computed tomographic angiography before intervention (2,3).

Several clinical studies performed during the past 3 decades have demonstrated the utility of acoustic methods for the diagnosis of arterial stenoses (4–7). Vascular sounds, or bruits, are audio frequency tissue vibrations caused by turbulent flow downstream of arterial stenoses. These vibrations propagate through the soft tissue surrounding the stenosis site. Quantitative analysis of the bruit, known as phonoangiography, has shown that the frequency of the bruit is related to the minimum stenosis diameter. We have developed a method, called Doppler vibrometry, to locate and quantify these tissue vibrations (8). Bruits appear in the spectral Doppler waveform as double-sided clutter (Fig 1). Conventional Doppler instruments attempt to suppress these tissue signals by employing wall filters. Doppler vibrometry enables the quantification of these tissue vibration signals from tissue near the stenosis site. Vibrometry is a significant improvement over phonoangiography, which is limited only to...
bruits audible at the skin and thus lacks specificity about the origin of the bruit. Vibrometry allows the measurement of vibration amplitude within the tissue adjacent to the artery, allowing computation of acoustic intensity as well as frequency. Vibrometry does not require visualization of the artery lumen yet can provide quantitative information about poststenotic turbulence. Thus, vibrometry can potentially complement duplex US in technically challenging cases. The purpose of this study was to correlate the quantitative vibration characteristics determined with Doppler vibrometry in abdominal and pelvic arteries with the stenosis severity determined with conventional angiography.

**MATERIALS AND METHODS**

**Study Population**

In this prospective feasibility study, 16 patients (eight women) who were scheduled to undergo abdominal or pelvic angiography at the University of Washington interventional radiology laboratory were recruited for examination before angiography. Angiography was indicated in these patients to evaluate suspected stenoses on the basis of a previous conventional duplex US examination. The symptoms that prompted the initial duplex examination were varied and related to different vascular beds (eg, hypertension, liver dysfunction, chronic abdominal discomfort, and claudication). Written informed consent was obtained from all patients. The University of Washington institutional review board approved all the study procedures.

**US Data Acquisition**

A commercial US instrument (Hi-Vision 5500; Hitachi Medical Systems America, Twinsburg, Ohio) was modified with custom software to acquire raw US data before conventional Doppler signal processing. A 3–5-MHz convex transducer was used to acquire data from a 15-mm range gate placed in the perivascular tissue proximal to stenoses, close to the most narrow lumen, and distal to the suspected stenoses in renal, hepatic, common iliac, and superior mesenteric arteries. The acquired Doppler data were synchronized with the R wave of the electrocardiographic signal. **Figure 2a.1** shows the approximate placement of the 15-mm Doppler range gate in the perivascular tissue surrounding a stenosis site in an iliac artery. The double-sided spectral signature of the bruit is clearly visible in the spectral Doppler waveform (**Fig 2a.2**).

**Quantification of Tissue Vibrations**

The raw US data were processed by using custom signal processing methods that have been described in detail elsewhere (8). These methods were designed to estimate and analyze the tissue motion surrounding the artery as opposed to the blood velocity inside the lumen. Briefly, the instantaneous tissue velocity was estimated by using a conventional autocorrelation method without employing any wall filters (**Fig 2b.1**). The velocity was integrated to obtain a tissue displacement signal. The audio frequency tissue vibration was isolated by filtering the tissue displacement signal between the frequencies of 100 and 1,000 Hz, which corresponds to the expected frequency range of poststenotic bruits (**Fig 2b.2**). The duration and frequency of the vibration signal were then quantified. The spectral waveform of the vibration demonstrates the broadband high-frequency content (**Fig 2b.3**). The frequency was estimated as the second moment of the vibration power spectral density (9).

**Quantification of Angiographic Severity**

Transcatheter digital subtraction angiography was performed in each patient by using the Axiom Artis dTA
(Siemens Medical Systems, Malvern, Pennsylvania) angiography system. A nonselective aortogram was obtained initially followed by selective angiograms of the vessel of interest. Imaging was done in multiple planes with a minimum of two orthogonal planes. The image that showed the lesion in the best profile was selected for measurements. Measurements were carried out by using the internal calibration standards preset in the equipment. The opacified luminal diameters were measured at the lesion as well as before and after the lesion. The measurements were done by one operator (S.V.), who was blinded to the results of the Doppler and vibrometry studies. In this study, the stenosis severity was treated as a continuous variable (percentage diameter reduction) and the correlation of the vibration characteristics with stenosis severity was estimated.

RESULTS

A total of 18 arteries were imaged in the 16 patients. Of the 18 arteries, stenoses (diameter reduction, 43%–91%) were angiographically measured in six renal arteries, four hepatic arteries, three iliac arteries, and one superior mesenteric artery yielding vibrometry data. One patient with a 79% diameter reduction hepatic artery stenosis did not yield measurable vibrometry data due to significant bowel gas precluding adequate US data acquisition. Three iliac arteries were normal (<30% diameter reduction at angiography).

Perivascular tissue velocities in angiographically normal arteries (<30% diameter reduction) did not show any significant vibrations (the frequency content of tissue displacement signals...
was <250 Hz). Figure 3a shows the vibrometry signals and spectral waveforms over one complete cardiac cycle from a representative common iliac artery with no angiographic stenosis. As the stenosis severity increases, the vibration frequency and duration increase. Figures 3b and 3c show representative vibrometry signals and spectral waveforms for two different severities of common iliac artery stenoses. Figure 4 shows scattergrams of the vibration frequency and duration versus the angiographic percentage stenosis and the reciprocal of the minimum lumen diameter. The vibration frequency was correlated with the percentage stenosis (Pearson $r = 0.75; P < .001$) and inversely correlated with the minimum lumen diameter ($r = 0.72; P < .001$). The correlation between the vibration duration and the percentage stenosis was 0.7 ($P < .001$). The vibration duration was correlated with the vibration frequency ($r = 0.82; P < .001$) (Fig 5). Stepwise regression showed that, among vibration frequency and duration, the vibration frequency was the primary independent significant predictor of the angiographic percentage stenosis ($P < .05$).

**DISCUSSION**

Lees and colleagues (4,10,11) developed the phonoangiography method for predicting the minimum lumen diameter of a carotid stenosis on the basis of a quantitative analysis of the frequency spectrum of cervical bruits detected on the skin surface. The hypothesis behind quantitative phonoangiography is that the frequency spectrum of the sound produced by vessel wall vibrations is dependent on the effective diameter of the turbulent jet, assuming that the systolic flow rate to the brain is the same in all patients. It was shown that the bruit spectrum exhibits a peak frequency beyond which the energy falls off rapidly with increasing frequency.

From theoretical fluid dynamic considerations, the break frequency of turbulent fluctuations is inversely proportional to the length scale of turbulence (the residual lumen diameter at the stenosis), provided that the Strouhal number and the mean downstream velocity (blood velocity in the unobstructed vessel) remain constant.

---

**Figure 4.** Scattergrams demonstrate the correlations between vibration characteristics and angiographic measurements. (a) Vibration frequency and percentage stenosis, (b) vibration frequency and reciprocal of minimum lumen diameter, (c) vibration duration and percentage stenosis, and (d) vibration duration and reciprocal of minimum lumen diameter.

**Figure 5.** Scattergram shows correlation between vibration duration and vibration frequency.
It was empirically observed that in the carotid arteries a simple relationship exists between the break frequency and the residual lumen diameter, by assuming that the unobstructed mean velocity in the carotid artery is approximately constant at 500 mm/sec \((6,11)\). The minimum lumen diameter (in millimeters) could then be obtained by dividing 500 by the break frequency (in hertz).

Several clinical studies demonstrated the validity of this method \((5–7)\), and it was shown that the effective residual lumen diameter in carotid artery stenoses was accurately estimated with this technique to within 1 mm of the angiographic value in 93% of 170 cases \((12)\). Several researchers have experimentally confirmed the production of vessel wall vibrations due to underlying flow turbulence \((9,13–15)\). However, phonoangiography lacks specificity about the source of the bruit. For example, a cervical bruit could be caused by an internal or external carotid stenosis or a conducted cardiac murmur \((6)\). In addition, a substantial number of bruits recorded at the skin surface are too weak to be analyzed \((6)\). These limitations made phonoangiography less attractive for routine clinical use compared to duplex Doppler US.

The presence of the bruit signature on spectral Doppler waveforms and color Doppler images is well known \((1,16–18)\). The common presentation of a bruit is a double-sided clutter on spectral Doppler waveforms and a focal random mixture of red (motion toward the US transducer) and blue (motion away from the transducer) colors forming a mosaic pattern on color Doppler images. The perivascular bruit artifacts have been shown to have clinical utility in the identification of hemodynamically significant stenoses \((19)\). Our results provide preliminary evidence that the vibration frequency estimated from the Doppler bruit spectrum can be used as a predictor of stenosis severity. Doppler vibrometry can complement conventional duplex examinations, especially in technically challenging cases, because vibrometry does not require visualization of the vessel lumen \((20)\). The measurements of the vibration frequency and duration with use of Doppler vibrometry are independent of the Doppler angle \((21)\). Furthermore, echoes from tissue are significantly stronger \((60 \text{ dB or more})\) than those from blood; thus, Doppler vibrometry can provide an advantage over duplex US in hard-to-image patients.

The vibration characteristics varied with the placement of the Doppler range gate. Figure 6 shows the change in the vibration characteristics as the Doppler range gate was placed upstream, immediately downstream, and farther downstream of a severe common iliac artery stenosis. The vibration amplitude is highest immediately downstream of the stenosis, as expected. Therefore, the vibration amplitude can be used as a guide for stenosis location. Downstream of the stenosis, the high-frequency components of the vibration are attenuated. This is expected because only the larger, lower-frequency eddies are convected downstream.

In addition to the frequency, the duration of the bruit has been proposed as an important diagnostic parameter \((7)\). In our present study, the vibration duration was correlated with the stenosis severity but did not have any additional predictive value for determining the angiographic severity compared with the vibration frequency. We believe that the duration of the bruit could be an indirect measure of the hemodynamically significant poststenotic pressure drop. The components of the pressure drop across the stenosis are the Bernoulli pressure depression due to an increase in velocity in the poststenotic jet and the viscous loss due to turbulence. The Bernoulli pressure depression is recovered as the flow velocity returns to normal farther downstream of the stenosis if turbulence is not present. The irrecoverable viscous loss due to turbulence is the component of the pressure drop...
that contributes to the reduction in the end organ flow. The pressure drop across the stenosis provides the energy to sustain turbulence in poststenotic flow and the resulting vibrations. Therefore, it may be argued that a short-duration vibration corresponds to a smaller pressure drop across the stenosis that occurs only during the peak systolic deceleration phase, whereas a longer-duration vibration corresponds to a larger pressure drop that is sustained for a longer duration in systole. Further studies are needed to confirm this hypothesis.

Although renal artery, iliac artery, and superior mesenteric artery stenoses showed good agreement with the overall trend, hepatic artery stenoses tended to be outliers both in terms of vibration frequency and duration (note the large variability of frequency and duration values for two 80% diameter reduction hepatic artery stenoses in Fig 4, and the case for which no measurable vibration data could be obtained). Figure 7 shows two stenoses of similar severity in the superior mesenteric artery and proper hepatic artery. The vibrations in the hepatic artery stenosis are significantly weaker. We believe that three factors could have potentially contributed to this: (a) the anatomic location of hepatic arteries and their lack of a close coupling with surrounding soft tissue compared to other arterial beds, such as renal and iliac; (b) substantial movement of the hepatic artery and surrounding tissues during respiration causing difficulties in placement of the range gate close to the stenosis region; and (c) the presence of bowel gas blocking the vibrometry signal, either preventing the acquisition of measurable data or leading to underestimation of the vibration frequency. Hepatic artery flow rates are also variable depending on the fasting state of the patient, which could explain some of the variability in the vibrometry findings (22).

One potential application of Doppler vibrometry could be as an adjunct to duplex US examination for renal artery stenosis. A major challenge for diagnosing renal artery stenosis with duplex US is the difficulty in visualizing renal arteries, especially in patients with substantial body fat. A further complication is the complex anatomy of the renal arteries in many patients due to the high prevalence of accessory renal arteries. Stenoses in accessory renal arteries could contribute to renovascular hypertension, yet they are often missed in routine duplex examinations. Furthermore, the Doppler range gate must be placed at multiple locations along the renal artery and renal parenchyma for a complete evaluation of all possible stenotic sites, which makes the examination time-consuming. In addition to these technical challenges, the choice of...
an appropriate diagnostic parameter for renal artery stenosis continues to be controversial because the commonly used parameters (eg, renal artery peak systolic velocity, renal aortic ratio, renal resistive index) have been shown to have limitations (23). Bruits have the highest positive predictive value among the clinical signs for renovascular disease (24,25) and are prevalent in 77%–87% of patients with angiographically proved renal artery stenosis. The diagnosis of renovascular hypertension with stethoscope auscultation of abdominal bruits has a high specificity (90%–99%) and a somewhat low sensitivity (39%–63%) compared with angiography (24). We believe that ultrasonic vibrometry could have greater sensitivity for the detection of abdominal bruits compared to stethoscope auscultation, which would increase the sensitivity of bruit analysis. In addition, the quantitative analysis of Doppler bruit frequency, duration, and amplitude would contribute to the clinical diagnosis of renal artery stenosis by providing complementary measurements to the conventional indexes on the basis of blood flow velocity.

Some limitations of our study should be acknowledged. The small sample size of this study prevented a detailed evaluation of the differences in vibration characteristics from different vascular beds. Future studies with a larger sample size are needed to determine the inter- and intraobserver variability and repeatability of the vibrometry method.

In conclusion, advances in Doppler technology and the development of diagnostic criteria based on blood flow velocities have overshadowed the clinical use of phonoangiography and quantitative analysis of bruits. However, the principles of phonoangiography can be applied to US echo signals and have the advantages of greater signal strength, no visualization of the vessel lumen, and no dependence on angle in situations where conventional Doppler methods have limitations. Our preliminary results show that quantitative analysis of Doppler bruits with vibrometry can be used to predict the severity of stenoses in renal, iliac, and superior mesenteric arteries.

References