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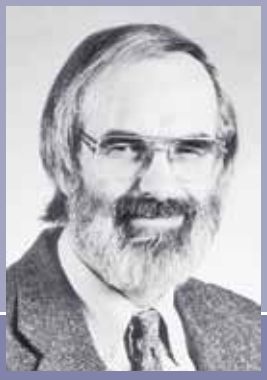
- Arterial Vibrometry
- Tissue Pulsatility Imaging of Brain
- Tissue Pulsatility Imaging of Placenta
- Multi-dimensional Doppler and Computational Hemodynamics
- Carotid Duplex Ultrasound Reading Center



Research Professor Emeritus

Half a century ago: when D. Eugene Strandness joined the University of Washington (UW) Department of Surgery as the Vascular Surgeon, Robert Rushmer, founder of Bioengineering at UW, was exploring cardiovascular physiology and Don Baker, using a newly available transistor, had just developed a portable ultrasonic Doppler for studies of blood flow at UW. Strandness collaborated with Rushmer and Baker to develop noninvasive diagnostic methods for arterial and venous diseases, leading the worldwide revolution in noninvasive diagnostic methods. To document these audio signals on paper for publication and teaching purposes, Strandness pioneered the use of spectrum analysis waveform display Doppler signals. By 1985, the Strandness team had established the guidelines for the modern duplex/Doppler spectrum analysis methods, which are still the standard. In addition to Doppler ultrasound, other diagnostic methods were used in the Strandness laboratory including: 1) plethysmography, measuring the normal 1% inflation and deflation of arterioles and venules in tissue with blood due to the cardiac cycle and respiratory cycle, and 2) phonoangiography, measuring the intensity and frequency of "bruits" (sounds generated by blood flow through arterial stenoses). These methods all depend on precise measurements of tissue motion.

The University of Washington Ultrasound Reading Center (UWURC) in the Strandness Vascular Laboratory has provided quality control for eight carotid stent studies including 15,182 examinations on 5,319 patients performed by more than 300 field centers.

In 1985, David Phillips demonstrated that tiny tissue motions (0.04 mm = 40 µm) could be monitored with ultrasound through the skin. Phillips measured the motions of arterial walls during the heart cycle. Since that time, ultrasound instruments have evolved, changing from analog systems using electronic circuitry to process signals into digital "PC" computer-based systems using computer programs to process signals. We can now easily modify the way ultrasound instruments acquire, process and display signals just by changing the computer program that operates the instrument. This has allowed us to develop and test new methods for examining tissue motions; we can now resolve motions as small as 0.1 µm.

Both plethysmography and phonoangiography are based on studying tissue motion: plethysmography studies tissue expansion with the cardiac and respiratory cycle; phonoangiography studies tissue vibration in the frequency range of hearing between 20 Hz and 1000 Hz. Traditionally, these methods are applied to a large body part such as arm, leg, finger, eye, skin and neck. However, by programming new methods of signal analysis into a conventional ultrasound instrument, these motions (expansion or vibration) can be measured inside the body, allowing the detection and characterization of vascular disease in organs and/or small regions of tissue.

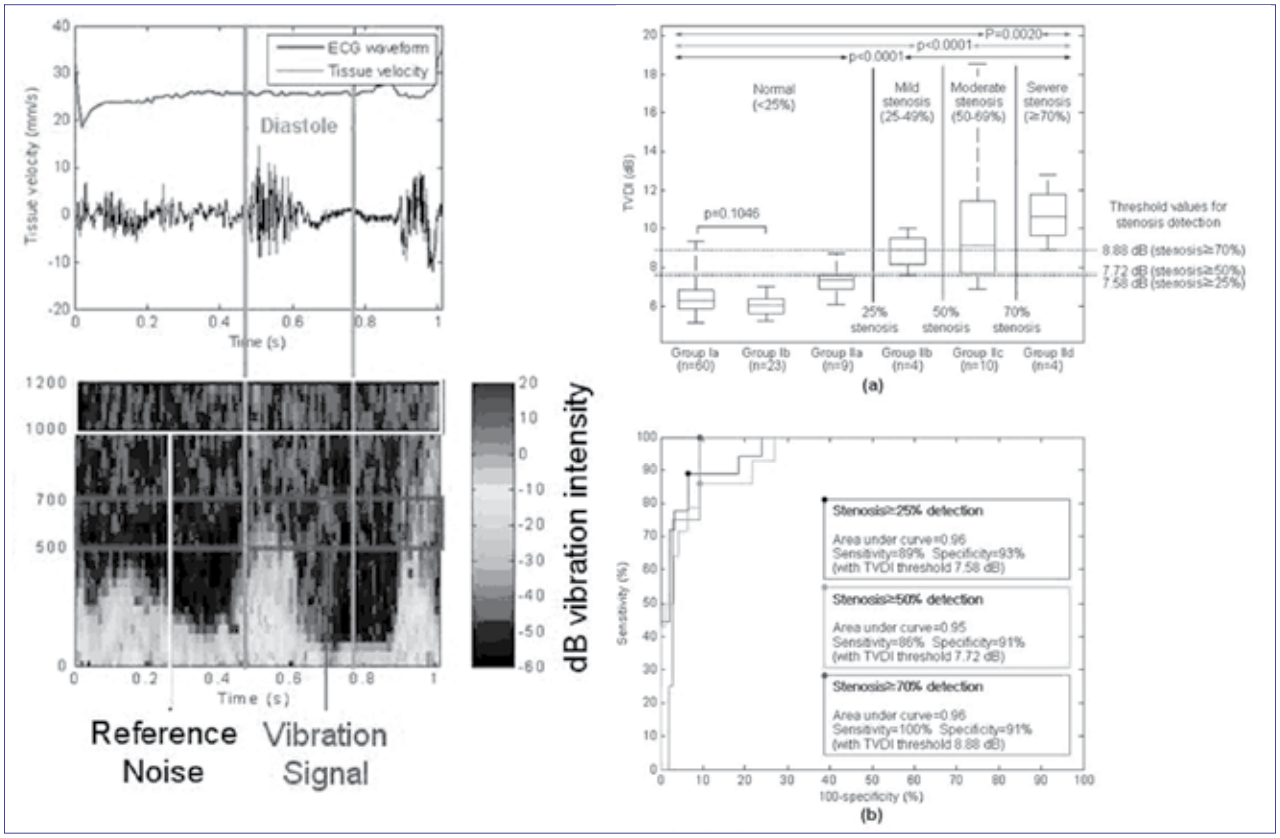


Figure 1 Left Anterior Descending Coronary Artery (LAD) Vibrometry

Left Upper: Velocity of heart muscle (vertical) near the LAD during the cardiac cycle showing the diastolic time window (between brown lines) used for analysis. Left coronary artery flow is high in diastole. The vibration at the beginning of diastole mark the stenosis.

Left Lower: Frequency spectrum of vibrations showing significant frequency band (red box) which is compared to a higher frequency noise band (black box). The vibration frequency in early diastole reaches 600 Hz.

Right Upper: Box and whisker plot of diastolic bruit (500 Hz to 700 Hz) intensity (vertical) vs coronary artery angiographic classification (horizontal)

Right Lower: Sensitivity and Specificity for different diagnostic bruit intensity thresholds.

Arterial Vibrometry

A stenosis in a major arterial pathway, which limits the blood pressure supplied to distal tissues, often causes a bruit (murmur) that can be heard through the skin with a stethoscope. These sounds are most easily heard if the stenosis is close to the skin. Bruits are often heard in the carotid arteries in the neck and femoral arteries in the leg. Although theoretically, a stenosis in a smaller, deeper artery will also emit a bruit, such bruits are rarely heard with a stethoscope because of the low intensity of the sound source and the attenuation through the tissue between the skin and the stenosis. However, an ultrasound system can detect small tissue motions at depths of 15 cm resolving vibrations with frequencies as high as 1200 Hz.

One important application is the detection of coronary artery stenosis. In collaboration with Professor Yongmin Kim in Bioengineering and a startup company who licensed the technology from the UW Center for Commercialization, the ability of vibrometry to detect coronary artery stenosis with vibrometry was tested by cardiologist Dr. Keith Comess (Figure 1).

In 16 of 18 cases with left anterior descending coronary artery stenosis, diastolic bruits were detected with frequencies between 500 and 700 Hz, but only 5 of 92 non-stenotic cases had similar bruits.

Although a variety of methods to detect coronary artery stenosis are already commonly used in clinical practice, non are used in front line primary care due to combinations of cost, risk, and lack of specificity. We think that coronary artery vibrometry can be implemented in an application-specific low-cost automatic ultrasonic instrument that will noninvasively identify the location of each coronary artery stenosis and grade the severity to provide a guide to the primary care physician for remedial therapy or referral.

Tissue Pulsatility Imaging of Brain

A significant arterial stenosis, in addition to causing a bruit, will also delay the transmission of the cardiac pulse to distal tissues by more than 50 milliseconds. This delay is large enough to be detected by pulse palpation on physical examination. Pulse delay can be measured with plethysmography between left and right legs, eyes or other body parts. Pulse delay can also be measured in deep tissues using a specially programmed ultrasound system.

Pulsations in brain tissues can be detected with ultrasound, and pulse delays can be measured separately in brain tissues supplied by the anterior, middle or posterior cerebral arteries. We believe that by detecting pulse delays in regions of the cerebral cortex, significant stenoses in the cerebral branch arteries above the circle of Willis can be identified. Preliminary studies with primitive signal processing show that pulsations can be measured; improvements in signal processing are needed to resolve significant pulse delay in the far hemisphere where data from larger regions of the cerebral cortex can be conveniently acquired.

Stenoses in the cerebral arteries can be detected by conventional MR and X-ray angiographic methods, but the cost and risk are prohibitive for screening purposes. Brain tissue pulsatility imaging can be implemented in an application-specific low-cost automatic ultrasonic instrument that noninvasively identifies the location of each hypotensive region of the brain distal to a stenosis and grades the severity to provide a guide to the primary care physician for remedial therapy or referral.

Tissue Pulsatility Imaging of Placenta

Placenta is a unique organ perfused by both maternal (low pulse rate) and fetal (high pulse rate) circulations (Figure 2). For nutrition to pass through the placenta to the fetal blood, each segment of the placenta must be perfused by both fetal and maternal circulations. By using tissue pulsatility imaging, both the maternal and fetal pulses can be detected. Graduate student Asanka Dewaraja, working with Tom Easterling and Mark Moehring, is testing regions of the placenta to measure both maternal and fetal pulsations.

If the fetal pulse is absent in a placental region, then nutrition from that maternal blood is not supplied to the fetus, and the vascular resistance of the placenta to fetal blood is increased. If the maternal pulse is absent in a placental region, then the fetal blood is not receiving nutrition from the maternal blood. In both cases, nutrition to the fetus is reduced. A map of the fetal and maternal pulsations in the placenta may provide early warning of placental dysfunction so that therapy can be instituted.

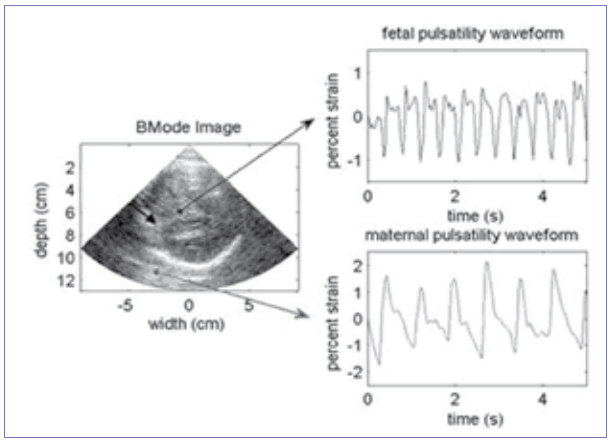


Figure 2 Tissue Pulsatility Image of Fetus, Image by John Kucewicz

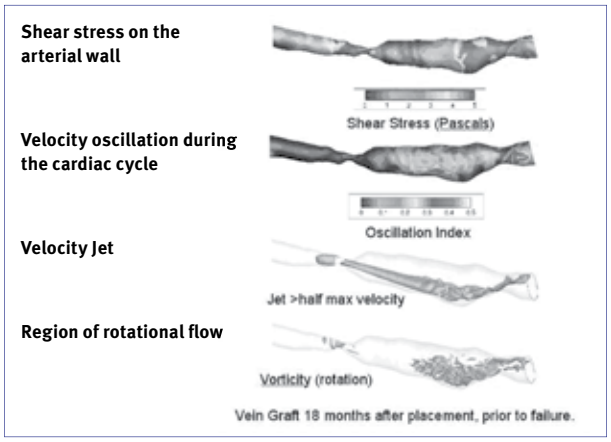


Figure 3 Computational Hemodynamics in Stenotic Vein Graft

Multi-dimensional Doppler and Computational Hemodynamics

Programmable ultrasound instruments also allow the detailed study of blood velocity vectors in three dimensions using an ultrasound system developed by Dan Leotta. This system provides new insight into the rapid fluctuations in complicated blood flow patterns. Now we are combining these anatomic and Doppler velocity details with fluid mechanical simulations developed by Alberto Aliseda in the Department of Mechanical Engineering to predict the forces applied to vascular walls in patients.

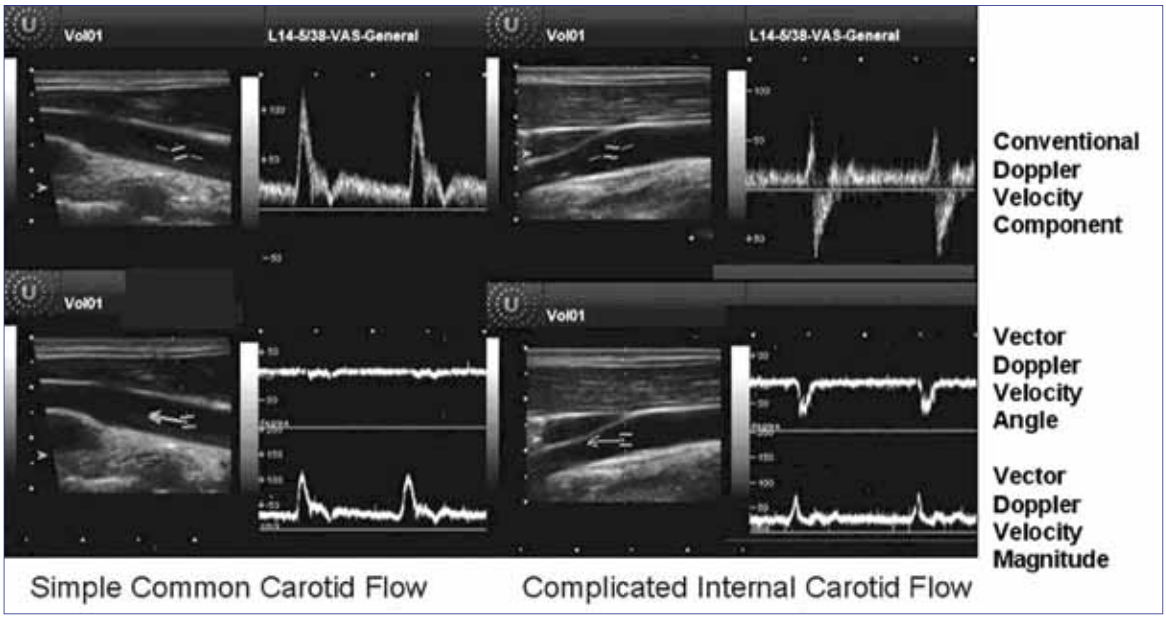


Figure 4 Conventional Doppler waveform compared to Vector Doppler waveform.

Left Upper: Conventional Doppler Common Carotid Artery waveform showing a 60 degree Doppler angle component of simple flow parallel to the artery axis.

Left Lower: Vector Doppler Common Carotid Artery waveform showing the blood velocity angle waveform and the velocity magnitude waveform.

Right Upper: Conventional Doppler Internal Carotid Artery waveform showing a 60 degree Doppler angle component of flow with a deceleration vortex, appearing as an apparent flow reversal.

Right Lower: Vector Doppler Internal Carotid Artery waveform showing the blood velocity angle waveform which changes during deceleration and the velocity magnitude waveform.

The 3-dimensional ultrasound images are used to provide a computational model of the shape vascular conduit. The conduit shape combined with the blood flow waveform, is processed with a computational fluid mechanics computer program to provide a detailed map of the flow including the impact of the blood on the wall (Figure 3).

According to published literature, either the hemodynamic shear on the vascular wall or the velocity oscillations stimulate remodeling of the arterial conduit wall. This remodeling will either lead to accommodation of the flow or to stenosis and occlusion. With serial 3-dimensional ultrasound studies correlating the hemodynamics computed at the wall with the remodeling of the wall, we hope to discern the effect of hemodynamic parameters on cellular proliferation, plaque formation and other remodeling factors.

At each examination, the computational hemodynamic results are correlated with detailed ultrasonic Doppler studies to assure that the computations correctly predict the flows that are actually present in the artery.

Although conventional ultrasonic Doppler measurements provide a component of the blood velocity that can be compared to the computations, more detailed Doppler data is now available using Vector Doppler (Figure 4).

Because of the high time resolution of the vector Doppler analysis, details of turbulence and actual wall shear stress can be measured for comparison with computations.

Carotid Duplex Ultrasound Reading Center

Over the last decade, a series of studies have been initiated to evaluate the treatment of carotid stenosis with stents. The University of Washington Ultrasound Reading Center (UWURC) in the Strandness Vascular Laboratory has provided quality control for eight carotid stent studies including 15,182 examinations on 5,319 patients performed by more than 300 field centers. The UWURC reviews all ultrasound images and waveforms, verifying locations, measurements and classifications from the source images.

Although carotid Doppler ultrasound has been widely used for over 25 years, questions still remain about exactly how the examinations should be performed and interpreted. Examiners disagree about whether Doppler signals should be acquired at a fixed Doppler angle of 60 degrees to the vessel axis or whether a variety of Doppler angles less than 60 degrees is preferable. A second question is how systolic velocity should be measured in waveforms with end-systolic deceleration turbulence.

Doppler velocity measurements are easily acquired at different angles from the same location in the carotid artery. This experiment shows that use of a higher Doppler angle results in a higher velocity value. Although this finding has stimulated discussion about which is the "correct" Doppler angle to get the "correct" velocity, none of the alternatives has resulted in superior correlation with carotid angiographic measurements. By exploring changes in velocity measurements within each patient over time, the UWURC will compute the variance of serial measurements for estimates of surveillance precision to determine how the selection of Doppler examination angle affects Doppler studies.

The interpretation of carotid Doppler waveforms has evolved empirically, adopting a logical policy so long as it appears to work. As a result, there is disagreement

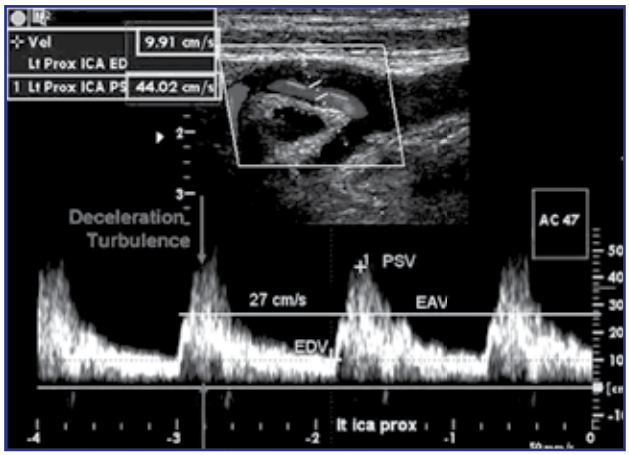


Figure 5 Doppler Waveform with End Acceleration Velocity

about exactly how to place the measurement cursors on some waveforms. When faced with turbulence during end-systolic deceleration, most examiners choose the highest value "peak systolic velocity (PSV) (Figure 5), but when deceleration turbulence is present, a lower end acceleration velocity (EAV) might be more appropriate. No comprehensive study has explored whether one choice should be preferred. By exploring changes in velocity measurements within each patient over time, the UWURC will tabulate whether deceleration turbulence is present in the same patient on repeat studies, and if so, whether choice of PSV or EAV provides the lowest variance between examinations.

Conclusion

The noninvasive vascular laboratory in the Department of Surgery has contributed to the long history of ultrasonic Doppler methods for vascular diagnosis. The close relationship between clinical practice and engineering innovation, pioneered by Gene Strandness when he founded the laboratory, is continuing to provide leadership in the development of instruments and methods that improve patient outcome.

RELATED PUBLICATIONS

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