Doppler color-flow images from a stenosed arterial model: Interpretation of flow patterns

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The capability of the recently introduced Doppler color-flow mapping devices to accurately detect flow patterns in the region of an arterial stenosis was evaluated by use of an in vitro flow model. Pulsatile flow simulating that in a low-resistance vessel was induced through a straight acrylic tube, which alternatively contained axisymmetric stenoses of 0%, 20%, 40%, 60%, and 80% diameter reduction. Doppler color-flow mapper images were taken in realtime along the tube midplane from 0 to 8 diameters downstream of each stenosis. Comparison of the Doppler color-flow mapping results with similarly recorded flow visualization (hydrogen bubble) images showed a close correspondence of key features of the flow, including detection of a high-velocity, centerline jet and near-wall separated flow zones. Distinctive flow patterns exist with each stenotic case, and these should be of considerable value in diagnosing clinical disease conditions. (J VASC SURG 1990;12:511-22.)

Adaptation of radar-based techniques developed for aviation purposes combined with the continued improvement in speed and capacity of data processing devices resulted in the introduction of the ultrasound Doppler color-flow mapping technique in 1983. Although it was initially applied to diagnosis of intracardiac defects, the Doppler color-flow mapping technique has been widely applied to peripheral vascular testing applications and is now accepted as a standard procedure in many major diagnostic centers, with considerable effort continuing to take place to identify all potential applications that exist for this technique.

Despite this feverish activity to establish a role for Doppler color-flow mapping in vascular diagnosis, little information remains on how to interpret the resultant images. In the diagnosis of vascular stenosis, most reports attempt to quantify or validate the Doppler color-flow mapping procedure by making comparisons of case study results to those of corresponding contrast arteriography. Although this approach does provide some measure of the ability of Doppler color-flow mapping to detect stenotic lesions, use of arteriographic (anatomic) data is a questionable means of validation for the flow (physiologic) information provided by color Doppler techniques. Therefore a central problem remains in simply understanding the basic fluid mechanics associated with vascular flow phenomena and then applying this knowledge to "translate" the color-flow images into diagnostically useful information. As a consequence a current limitation of Doppler color-flow mapping is the lack of standardized methods for interpretation of the color images.

It is the purpose of this article to present results from a stenotic artery model that directly compares detailed observations of flow patterns by flow visualization methods to corresponding Doppler color-flow mapping images to provide a hemodynamic basis for better understanding and validating this new technique.

METHODS

The flow model consisted of a straight 22 mm inner diameter (I.D.), 29 cm long acrylic tube. A series of axisymmetric stenotic plugs producing 0% (0%), 20% (36%), 40% (64%), 60% (84%), and 80% (96%) diameter (cross-sectional area) reductions were sequentially placed within the tube 5 cm from the inlet. These stenotic plugs were custom-made from a solid 22 mm diameter acrylic rod to produce a gradually rounded, smooth shape in each case. A second straight tube 16 mm I.D., 22 mm outer diameter (O.D.) and 17.5 cm long was inserted into the larger tube to provide a smooth interface with the stenotic plugs and resulted in an effective
Fig. 1. Pulsatile flow model system with stenotic test section, hydrogen bubble flow visualization technique, and Doppler color-flow mapping device.

diameter of 16 mm. The entire test section was held in a 29 cm × 5 cm × 15 cm acrylic viewing tank and submerged in mineral oil (paraffin oil, heavy [Fisher Scientific Co., Pittsburgh, Pa.] refractive index = 1.482) to minimize effects of optical refraction as compared to the acrylic (refractive index ranging from 1.489 to 1.492).

The test section was incorporated into a pulsatile flow system (Fig. 1) consisting of (1) a diaphragm pump, (2) a bypass to the return reservoir, (3) variable compliance chambers, (4) a laminar flow resistor, (5) electrolysis anode and cathode filaments, (6) a pressure port, (7) an electromagnetic flow transducer, (7) a variable resistor, and (8) a return reservoir. The flow system was filled with a 3.5% dextran and distilled water solution, which produced a kinematic viscosity of 3.5 cp. Potassium sulfate was added (0.4 mg/L) to increase the electrical conductivity of the fluid for the flow visualization recordings and 50 to 150 μm particles (Sephadex G-25 [Pharmacia Fine Chemicals, Piscataway, N.J.) were added to act as ultrasonic reflectors for the Doppler color-flow mapping. The diaphragm pump was actuated by compressed air (operating between 10 and 16 psi), which was pulsed on and off by a timer controlled solenoid valve. Flow direction was maintained by inlet and outlet disc-type valves. The system operated at 0.25 Hz, which resulted in a Womersley parameter of 5.36, which compares to that in a human internal carotid artery of diameter 7.3 mm at a heart rate of 72 beats per minute. The flow waveform was shaped to provide a pattern similar to that found in low-resistance vessels (i.e., carotid or renal arteries) by adjustment of the compliance in each cylindrical chamber and the downstream resistor. The flow rate was monitored by an electromagnetic flow meter (Model 700-1500, Narco Scientific, Houston, Texas) by use of a 12 mm cannulating probe and was set to a mean flow rate of 1 L/min and a maximum of 3 L/min, yielding mean and peak Reynolds numbers of 379 and 1137, respectively. As successive stenotic plugs were inserted into the test section, this mean flow rate was maintained constant while allowing some change in the waveform shape to occur.

Flow visualization was accomplished by means of hydrogen bubble markers produced by electrolysis at cathode filaments placed either upstream or just downstream of the stenotic plug. The hydrogen bubble technique was used to provide a visual impression of flow phenomena and to aid in the interpretation of laser Doppler velocity measurements in a follow-up study. The hydrogen bubbles were produced by use of a direct current between the cathode and anode (20 V direct current at a current of 10 mA.) both
continuously (for streamline patterns) and intermittently (for velocity profiles) by means of the time controlled signal that triggered the diaphragm pump. The bubbles were illuminated by a high-intensity lamp projecting through a narrow slit to produce a plane of light along the horizontal midplane of the test section. Still pictures were taken with a 35 mm camera (Minolta SR T-100 [Minolta Camera Co., Ltd., Osaka, Japan]) with a 50 mm lens and high-speed film (Kodak Ektachrome ASA 800/1600 [Eastman Kodak Co., Rochester, N.Y.]) at an f-stop of 3.5 and shutter speed of 1/60 s. Motion pictures were taken with a high-resolution (768H × 493V) GCD video camera (Sony XC-77 [Sony Medical Electronics, Park Ridge, N.J.]) with a zoom lens and super VHS recorder (Hitachi VT 2700A [Hitachi Denshi America, Ltd., Woodbury, N.Y.]). All recordings were taken along the horizontal midplane of the tube from the throat of the stenosis up to 5 diameters downstream and were viewed from below the section to avoid clouding by hydrogen bubbles that had risen to the upper tube surface.

Doppler color-flow mapping was performed by use of a real-time ultrasound Doppler color-flow mapping system (Computed Sonography 128, Acuson Inc., Mountain View, Calif.). Measurements on the 0% to 60% stenosis models were performed by use of a 7 MHz (model 7384) linear array transducer, whereas measurements made on the 80% stenosis model were made with a 5 MHz (model 538) linear array transducer. Each transducer was positioned above the test section along the midplane of the tube and immersed in the mineral oil bath. Images were then recorded over a 4 cm distance downstream of the outlet of each stenosis. Doppler color images used a hue representation at maximum saturation (V4 format) with recordings being made on a super VHS videotape recorder (Hitachi VT 2700A) as well as being fed to a color printer (Sony color printer). Because of unwanted reverberations within the upper wall of the tube, adequate images could only be obtained from the midline to the bottom of the tube in each case.

RESULTS

Flow visualization

For all of the stenotic conditions the inlet flow upstream of the stenotic plug was uniformly laminar, axially directed, and demonstrated a fully developed, pulsatile velocity profile. The flow patterns at, and downstream of, the stenotic plugs varied widely throughout the flow cycle as follows:

0% Stenosis. The flow exhibited the classic pattern seen with pulsating flow in a long rigid tube; namely, laminar, fully developed quasi-parabolic velocity profiles with no variation along the length of the tube. All regions exhibited continuous forward and axially directed velocity during the entire cycle, reaching a peak within 30 degrees from the pump trigger and slowing to zero velocity at the end of the cycle.

20% Stenosis. Flow entering the stenosis was accelerated and exhibited a slight convergence with velocities in most regions at and downstream of the stenosis, being continuously forward and slowing to zero at end cycle (Fig. 2). A boundary layer separation point occurred at one half diameter downstream from the throat of the stenosis. The central flow out of the throat moved rapidly and its circular stream waist expanded radially between 1 diameter and 2 diameters downstream from the throat pro-
Fig. 3. Diagram of hydrogen bubble flow visualization images up to 5 diameters downstream from a symmetric 40% diameter reduction. Flow sequence is shown from top to bottom as just before peak systole, peak systole, mid-deceleration phase, and late diastole, respectively.

Providing momentum for flow recirculation. There was a "necking" effect of the main profile as the outflow stream progressed further downstream, giving an appearance similar to a "mushroom head" with a long cylindrical stem. This was most pronounced at approximately 5.5 diameters from the stenosis with the width of the bubble-free zone accounting for 25% of the tube diameter along each wall. A large circular vortex was produced at the neck of the mushroom head, and it was observed that hydrogen bubbles in the vortex did not move back to the upstream separation zones after the vortex dissipated in diastole. Within these separation zones, reverse flow was initiated near the tube wall almost immediately after onset of the peak forward center-line velocity. Strong reverse flow was seen during the deceleration phase of the cycle and extended upstream toward the throat of the stenosis. No random, turbulent motions were seen anywhere within this test case.

40% Stenosis. Flow entering the stenosis as a jet stream with a boundary layer separation point occurring at the throat. The length of the central jet and the separation zones extended to 5 diameters from the throat during late cycle. The central axial jet dissipated as about 3 diameters downstream during the early acceleration phase giving way to a mixing zone where the flow broke up into strong secondary motions. A short time later, a necking effect was observed at about 3.6 diameters downstream from the stenosis producing a mushroom head pattern, which occupied about 40% of the tube diameter along both walls. Large separation zones nearly equal to the stenotic elevation were seen along the tube walls, remaining constant in size until the end of diastole. Within these separation zones, reverse flow was initiated near the tube wall almost immediately after onset of the peak forward center-line velocity. Strong reverse flow was seen during the deceleration phase of the cycle and extended upstream toward the throat of the stenosis. No random, turbulent motions were seen anywhere within this test case.

60% Stenosis. Once again, acceleration and sharp convergence of flow was observed downstream of the stenotic plug with creation of a distinct central jet and separation zones (Fig. 4). The jet length extended 3.6 diameters from the end of the stenosis at peak velocity and terminated in a region of intense mixing. Large separation zones occupied a width of 0.3 diameter along either tube wall and stretched to a maximum distance of 4 diameters from the stenosis throat at about 88 degrees of the pump cycle (early deceleration phase). Chaotic, probably turbulent, mixing occurred throughout the region downstream of the jet head (4 diameter to 5 diameter region) during systole, and reverse flow was seen to form in this region at end of systole. The central jet and the flow separation zones slowly extended to 6 diameters (not shown) during diastole, and there were coherent eddies within the separated zones. The mushroom head phenomenon at the leading edge of the jet was not observed in this model.

80% Stenosis. Flow entering this stenotic plug experienced an extremely sharp convergence that resulted in a very fine central jet and distinct separation zones of the same size as the stenosis elevation (~0.4 diameter (Fig. 5). The jet length extended only about 2 diameters from the end of the stenosis at peak velocity and appeared to be laminar for a short distance before breaking up into turbulent mixing flow throughout virtually all regions downstream. This was chiefly seen during the systolic period (0 to 160 degrees within the cycle) with the jet length extend-
Fig. 4. Diagram of hydrogen bubble flow visualization images up to 5 diameters downstream from a symmetric 60% diameter reduction. Flow sequence is shown from top to bottom as just before peak systole, peak systole, mid-deceleration phase, and late diastole, respectively.

Fig. 5. Diagram of hydrogen bubble flow visualization images up to 5 diameters downstream from a symmetric 80% diameter reduction. Flow sequence is shown from top to bottom as just before peak systole, peak systole, mid-deceleration phase, and late diastole, respectively.

ing to greater distances during the late outflow (pump filling) phase. Strong secondary motions as well as numerous, small vortexes were seen within the separation zones. Clear evidence was seen of flow reversal in the separated zones with individual bubbles moving upstream along the tube walls. Velocities in the body of the separated zones appeared to be high and multidirectional as evidenced by randomly directed bubble streaks.

**Doppler color-flow mapping**

The Doppler color-flow images are shown in Figs. 6 through 10. In each case, a measurement “window” was selected that displays velocities within one half of the tube diameter from the centerline (top) to the tube wall (bottom) over a distance of 4 cm downstream at an angle of 72 degrees to the tube axis. Doppler color-flow images were collected over a distance of approximately 18 cm downstream of the throat of each stenosis but are only shown for the region from 0 to 2 diameters downstream of the throat of the stenosis. Furthermore, color-flow images were collected at four time intervals within the cycle starting at the moment of peak velocity and at successive 1 second intervals (one quarter cycle, or, 90 degrees cycle phase) thereafter. The color scale indicates velocities along the beam of the transducer and ranges up to 96 cm/second with the specific color bar shown to the left side in each figure.

**0% Stenosis.** The color-flow maps for the 0% stenosis case are shown in Fig. 6 with the color scale being from $-9$ cm/second (blue) to 15 cm/second (red). A uniform velocity pattern was observed along
the axial direction with all flow being displayed in various shades of red, signifying a forward direction. At peak flow (Fig. 6, a) there was a more yellowish hue toward the tube centerline, indicating higher velocities (approximately 15 cm/second), with a deepening shade of red toward the tube wall, indicating lower velocities. This pattern changed with the flow cycle as velocities throughout the section slowed, producing a uniform deepening of the red hue (Fig. 6, b). Virtually no indication was found of reverse flow, although a slight region of blackness was found along the tube wall at both the one half and three quarter cycle intervals (Fig. 6, c and d, respectively) as a result of the limited sensitivity of the system to very low velocities.

20% Stenosis. In the case of the 20% stenosis (Fig. 7), the color scale has been increased to accommodate somewhat higher velocities, ranging from −38 cm/second (blue) to 60 cm/second (red). Again, the color pattern is uniform in the axial direction downstream of the stenosis, and a gradual change occurs in hue from lighter shades near the tube center to darker shades along the tube wall during the first half cycle (Fig. 7, a and b). The magnitude of velocity is only slightly increased from those seen in the unstenosed (0%) case. Some blue speckling was seen near the tube wall at one half and three quarter cycle intervals (Fig. 7, c and d), indicating transient flow reversal.

40% Stenosis. The color-flow maps for the 40% stenosis case are shown in Fig. 8 with the color scale ranging from −16 cm/second (blue) to 48 cm/second (red). Again, color shades are lighter at peak velocity (Fig. 8, a) compared to those at three quarter cycle (Fig. 8, d), and they are lighter at the tube centerline compared to near the tube wall. However,
distinct changes in hue are found along the axial direction at each time interval. This is due to the diminishing width of flow separation zones along the tube wall with distance downstream. With the exception of the peak velocity interval (Fig. 8, a), these regions are displayed entirely in black, indicating only that the velocity magnitude is below approximately 3 cm/second but without specifying a definitive direction.

60% Stenosis. The color-flow maps for the 60% stenosis case are shown in Fig. 9 with the color scale ranging from −48 cm/second (blue) to 80 cm/second (red). Once again, color shades are lighter at peak velocity (Fig. 9, a) compared to those at three quarter cycle (Fig. 9, d), and they are generally lighter at the tube centerline compared to near the tube wall. A more heterogeneous mixture of light and dark red shades is seen at the 0 and one quarter cycle intervals, however, indicating a disturbed flow pattern. Distinct changes in hue also occur along the axial direction at each time interval because of the diminishing width of flow separation zones along the tube wall with distance downstream. A large separation zone is seen to grow during the last three quarters of the cycle, exhibiting relatively high reverse velocities especially at one quarter cycle interval. The display does not indicate turbulent flow since there is not an extreme speckling of colors with a mosaic pattern of sudden color reversals (red/blue mixtures) in any region. There is a sharp transition from red to blue, indicating the distinct boundary between the forward moving central jet and the reverse moving separated flow region along the outer wall.

80% Stenosis. The color-flow maps for the 80% stenosis case are shown in Fig. 10 with the color scale being −32 cm/second (blue) to 96 cm/second (red).
Fig. 8. Doppler color-flow maps up to 2 diameters downstream of a 40% stenosis. The measurement "window" displays velocities within one half of the tube diameter from the centerline (top) to the tube wall (bottom) over a distance of 4 cm downstream. Doppler color-flow mapping images are shown at four time intervals within the flow cycle starting at peak velocity (a) and at successive one quarter cycle intervals (b-d). Velocity ranges from −16 cm/second (blue) to 48 cm/second (red).

Once again, color shades are lighter at peak velocity (Fig. 10, a) compared to those at three quarter cycle (Fig. 10, d), and they are generally lighter at the tube centerline compared to those near the tube wall. A more heterogeneous mixture of light and dark red shades is seen at the 0 and one quarter cycle intervals, however, indicating a disturbed flow pattern. Distinct changes in hue also occur along the axial direction at each time interval because of the diminishing width of flow separation zones with distance downstream. A large separation zone is seen to grow during the last three quarters of the cycle, which exhibits relatively high reverse velocities, especially at one quarter cycle interval. A speckle pattern is also observed, especially at the one quarter and one half cycle intervals, indicating a rapid mixing of flow characteristic of turbulence. A large separation zone occurs along the tube wall with a distinct boundary between the forward directed velocity in the jet and the reverse flow in the separated zone.

DISCUSSION

It should be pointed out that the stenoses modeled in this study do not precisely represent "typical" clinical cases, and therefore further work must be done to provide methods for the detection of realistic stenoses which are potentially asymmetric, irregular, ulcerated, and the like. However, the present model does succeed in generating basic hemodynamic flow characteristics that are typical of those associated with stenosis.

As has been already established under steady flow conditions, velocity patterns vary measurably within a confined region at, and downstream of, a stenosis. Virtually the same predominant flow characteristics, namely creation of a flow jet, presence of
Fig. 9. Doppler color-flow maps up to 2 diameters downstream of a 60% stenosis. The measurement "window" displays velocities within one half of the tube diameter from the centerline (top) to the tube wall (bottom) over a distance of 4 cm downstream. Doppler color-flow mapping images are shown at four time intervals within the flow cycle starting at peak velocity (a) and at successive one quarter cycle intervals (b-d). Velocity ranges from -48 cm/second (blue) to 80 cm/second (red).

separated flow zones, flow reversal, and turbulence have been observed in the present pulsatile study. Significant differences from steady flow results, however, are noted in that the peak jet velocities are higher, separation zones are larger, and flow reversal is more evident at lower degrees of stenosis. As opposed to the steady flow model where turbulence is only observed in the 80% stenosis case, under pulsatile conditions turbulence is first seen in the 60% stenosis case at the time of peak velocity and in the 80% case throughout much of the pump cycle. The jet length is observed to be longer at peak forward flow for all stenotic cases. Strikingly similar flow patterns have been observed by Ojha et al.\textsuperscript{14} using a photochromic dye flow visualization technique. Their results for a 45% area reduction stenosis showed the same tendency for a flattened profile and shear layer disturbances as in the present 20% diameter reduction stenosis (36% area reduction) whereas their results for both 65% and 75% area reduction stenoses show a central jet and clear evidence of near wall flow reversal as is seen in the present 40% (64% area reduction) and 60% (84% area reduction) diameter stenoses.

In the present study comparison of the Doppler color-flow mapping results with the corresponding hydrogen bubble flow visualization results shows that there is a direct correlation of the hemodynamic features detected by both methods. In the unstenosed case both techniques depicted a uniform velocity field along the tube axis while clearly displaying a gradual but marked change in velocity with radial position across the tube, features consistent with an expected quasi-parabolic velocity profile. These findings persisted throughout the flow cycle with only a reduction in their magnitude as the flow subsided.

In all of the stenosed cases (20% to 80% diameter reductions), the Doppler color-flow mapping technique detected alterations in flow patterns as a result of presence of an upstream constriction, namely, (1) jet formation at, and immediately downstream of, the stenosis throat and (2) presence of flow separa-
Fig. 10. Doppler color-flow maps up to 2 diameters downstream of a 80% stenosis. The measurement “window” displays velocities within one half of the tube diameter from the centerline (top) to the tube wall (bottom) over a distance of 4 cm downstream. Doppler color-flow mapping images are shown at four time intervals within the flow cycle starting at peak velocity (a) and at successive one quarter cycle intervals (b-d). Velocity ranges from −32 cm/second (blue) to 96 cm/second (red).

The differentiation, zones near the vessel wall, again just downstream of the stenosis. Flow patterns associated with the 20% and 40% stenoses included a radial color gradient and varying indications of flow reversal during the latter stages of the flow cycle. Furthermore, the Doppler color-flow mapping images associated with the 60% and 80% stenoses exhibited much more heterogeneous color patterns with a distinct combination of high centerline flow and large reversals near the wall. A mixed pattern of red-to-yellow also occurs in the main stream indicating rapid local changes in either velocity or direction or both. The 80% stenosis is the most chaotic case, and its images demonstrate a large separated flow zone, which persists from early in the cycle throughout the remainder of the cycle. The deep reds that appear in the central jet alongside bright yells, again, are likely due to random changes in direction of flow particles, which gives rise to artificially reduced velocity magnitudes. Little indication of aliasing is found in these cases, which would be seen as isolated regions of reverse flow within forward flow, or blue on red. This is mainly due to the lower velocities seen in the flow model as a result of the tube scale factor used (∼7.5:1) to achieve greater resolution. In clinical practice, higher local velocities would be expected, which could exceed the maximum detection capability of the Doppler color-flow mapping device.

Based on the above features, it is possible to accurately locate the site and quantify the degree of stenosis in each of these cases. It is interesting to note that differentiation between stenosis degree is best
determined from flow patterns observed during late systole or diastole. These results compare well with Doppler color-flow mapping images of varying degrees of carotid artery stenosis cited by Middleton et al.9 In their study center stream flow velocity became increasingly elevated with the degree of stenosis, and a flow jet was clearly evident with stenoses of 80% or greater. Flow reversals were seen just downstream of stenoses of approximately 50% diameter reduction, particularly for short, sharply curved lesions, and a helical flow pattern of forward and reversed flow was observed downstream of high-grade (>85%) lesions. An exception to the above discussion is the unique case of flow patterns within the carotid artery bifurcation. Zierler et al.15 have documented the presence of flow reversals along the outer (posteriolateral) wall of the internal carotid artery in 10 healthy individuals. In this case flow reversal is a normal hemodynamic feature and is due to the widened bulb region of the proximal internal carotid artery. Its presence is, however, distinct from the flow reversals seen downstream of stenoses because (1) it generally occurs in a predictable location, (2) it is not associated with local elevations of centerstream velocity, and (3) there is not a rapid deceleration of centerstream velocity with further distance downstream of the region.

In conclusion, ultrasonic Doppler color-flow mapping is capable of detecting characteristic features of flow downstream of mild to severe stenoses and of presenting those features in real time. Specifically, Doppler color-flow mapping of poststenotic flows in the present pulsatile model provided detection of the following: (1) Overall character of flow that is, whether it is laminar, disturbed, or turbulent. (2) Elevated velocities seen within stenotic jets. (3) Reversed velocities within separated flow regions. (4) Rapid phasic changes in velocity occurring throughout the cardiac cycle.

The most significant aspect of the Doppler color-flow mapping technique is its unique ability to provide a real-time, full field view of flow in a selected region. Because of this, the resultant image is capable of displaying a combination of all of the above flow characteristics and thus allows a ready evaluation of key features. For example, it is possible to immediately identify elevated velocities in a jet flow region and to determine the site and extent of jetting. Separated flow zones, which are frequently occurring consequences of jet flow, would also be detected and their size and location determined. This full field capability is particularly useful in determining placement of a single channel pulse Doppler sample volume for further detailed analysis of velocity spectra at a specific site of interest. Availability of a full field view also enables the operator to better confirm the presence of velocity aliasing by comparing individual pixel colors with those of neighboring points and looking for unexplained, sudden reversals. It is also easier to interpolate flow characteristics within "dead", sonopaque zones by having information available from nearby upstream and downstream sites. Beyond the identification of distinct flow characteristics, Doppler color-flow mapping can be extremely valuable in detecting structural boundaries through its ability to discriminate between flowing and stationary objects. Thus the definition of vessel wall surfaces, edges of irregular or ulcerated plaques, and boundaries of fresh clot or intimal hyperplasia will be much more precise.

One limitation of the Doppler color-flow mapping system is that accurate detection of Doppler-derived flow velocities will be affected by any changes in direction from an assumed course parallel to the vessel axis. This error is a likely cause of some of the speckled colors seen in images downstream of the 60% and 80% stenoses where rotational motions were detected by flow visualization. In general, this effect may also occur in curved or branched vessels or in situations where flow is redirected as it passes through a diseased region. The resultant effect would be to cause various flow artifacts such as excessively elevated or reduced jet velocities or altered (expanded or contracted) separation zone sizes. Although the finite scan time was less than 1% of the cycle period in this model study, it could lead to significant changes in clinical images, especially in high velocity, severe stenoses. However, (1) these cases are typically the ones that are most readily identified, and (2) by use of restricted viewing windows the scan time can be significantly reduced.

Finally, presentation of such a large amount of information by the Doppler color-flow mapping frequently causes a sensory overload for the observer with the result that data become extremely difficult to analyze. Although initial work has been performed on quantifying flow patterns associated with cardiac septal and valvular abnormalities,16-18 no studies to date have quantitatively examined Doppler color-flow mapping images in the region of an arterial stenosis. It is our intention to perform further analysis of the present color images to define condensed indexes sensitive to the predominant features of each pattern. If this can be accomplished, then interpre-
tation of color-flow images will become faster, more accurate, and more consistent between different observers.

The authors acknowledge Hari Vattyam, BS, for his technical support and Acuson, Inc. for providing loaner equipment used in this project.

REFERENCES