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Doppler Color Flow Imaging

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Abstract: By simultaneous processing of frequency, phase, and amplitude information in the backscattered ultrasound signal, new instruments now permit the real-time display of high-resolution grey scale images of tissue combined with the simultaneous display of flow data from vessels within the scan plane. Doppler Color Flow Imaging, or DCFI, using such processing, permits blood flow direction and relative velocity to be detected and displayed in a color encoded display from throughout the ultrasound image. We have tested a new Doppler color flow imaging system over a period of two years to evaluate the carotid arteries, peripheral arteries and veins, and dialysis fistulas. In the abdomen and pelvis we have imaged blood flow to the liver, spleen, kidneys, uterus and renal transplants. Our experience in over 500 patients leads us to conclude that DCFI has significant advantages over conventional duplex Doppler sonography for blood flow evaluation. For examination of carotid and peripheral vessels, we have found DCFI to permit more rapid assessment in both normal and abnormal states. Areas of vessel narrowing or turbulent flow may be identified rapidly and accurately, and vessel orientation may be determined precisely, allowing accurate calculation of blood flow velocity from Doppler frequency shifts. The system we have used has adequate penetration and sensitivity to allow imaging of hepatic and renal blood flow and is extremely promising as a method of imaging organ perfusion and in the detection of abnormalities of perfusion that accompany disease, such as transplant rejection. Tumor vascularity may also be identified with DCFI, opening the possibilty of additional clinical applications.

The development of diagnostic ultrasonography has been marked by a series of major technological steps. The first of these was the transition from A-mode to B-mode display of the ultrasound signal, followed by the introduction of grey scale imaging in the early 1970s. Later in the 1970s real-time imaging became commercially available, making possible a new range of applications. Each of these steps has resulted in major improvements in the clinical utility of ultrasound for diagnosis. The most recent technological development likely to have major impact is the introduction of methods to process both tissue and flow data simultaneously from the backscattered ultrasound signal. This capability is now being realized in commercially available instruments that allow real-time simultaneous display of color-encoded flow along with high-resolution tissue detail.

The determination of vessel patency, blood flow, and organ perfusion has been a goal of diagnostic imaging since the turn of the century. This need has been addressed, with varying success, by angiography, dynamic computed tomography, radionuclide flow imaging, and magnetic resonance imaging, as well as Doppler ultrasonography. Despite the fact that conventional Doppler ultrasound has been used clinically for over 20 years, the role of Doppler ultrasound has evolved relatively slowly when compared to the rapid strides in other applications of diagnostic ultrasound. Most of the interest in Doppler ultrasound has resulted from the development of duplex scanners, which combine B-mode and Doppler for both tissue imaging and flow measurements. Despite significant advances, however, the use of Doppler ultrasound has been restricted to a relatively few well-defined indications in cardiac diagnosis, in the evaluation of carotid and peripheral vascular disease, and more recently in obstetrics and the abdomen.[1]

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A major limitation of duplex ultrasonic imaging is that flow information is obtained only from the highly restricted region from which the Doppler signals are sampled, and flow is not evaluated in the remainder of the image. Therefore, to obtain maximum information with duplex Doppler ultrasound, a skilled operator must perform careful sampling of the sites within the vessel lumen where flow disturbances are most likely to be found. A preferable approach would be a method allowing evaluation of flow characteristics throughout the entire image combined with high-resolution display of the vessel wall and surrounding tissue features. Many of these goals are met by a new method of combined Doppler flow and tissue imaging that, in order to distinguish it from earlier efforts at combined tissue and flow imaging, has been called Doppler color flow imaging (DCFI) or angiodynography.

A growing interest in the use of Doppler techniques for abdominal, pelvic, obstetrical, and oncologic applications, as well as in the evaluation of the carotid and peripheral vascular systems, makes the introduction of Doppler color flow imaging especially timely. Over the past four to five years we have followed the development of this technique and have tested DCFI in a range of clinical applications over the past 18 months. Our studies were performed with prototype and production versions of the Quantum Angio-Dynograph 1 (Quantum Medical Systems Inc., Issaguah, WA). Our experience indicates the potential for a major role of this new approach to ultrasound imaging, not only for carotid, cardiac, and peripheral arterial and venous applications, but also in the evaluation of deep vessels in the abdomen, pelvis, fetus, and for investigation of organ and tumor perfusion.

DOPPLER COLOR FLOW IMAGING: PRINCIPLES AND INSTRUMENTATION

In conventional B-mode ultrasound imaging, pulse-echo transmission, detection, and display techniques are used. In this form of imaging, only the amplitude information in the returning signal is used to generate the final display. Rapidly moving, low-amplitude targets, such as red cells moving in vessels, are not commonly displayed. As a consequence of the Doppler effect, the signal reflected from a moving interface contains frequency as well as amplitude information. With conventional Doppler instrumentation, the Doppler frequency information may be displayed as an audible signal for analysis by ear (an approach not suitable for quantitative assessment), or more commonly in graphic form as a time-varying plot of the frequency spectrum of the returning signal; in color flow systems this information is displayed in the image itself.

The DCFI system we have used employs a linear phased array to detect echo amplitude, phase, and frequency, and processes this information in real time to generate the image. Stationary or slowly moving targets provide the basis for the B-mode imaging. Signal phase provides information about the presence and direction of motion, and changes in echo signal frequency are related to the velocity of the target. Transducers operating at 7.5 MHz or 5.0 MHz are used. The 7.5-MHz transducer is useful for carotid and other superficial vessels and organs (including thyroid, testicle, breast, and pediatric cranial and abdominal applications). The 5.0-MHz transducer is suitable for deep abdominal and pelvic imaging, with penetration to approximately 14 cm. Continuous focusing is provided by the phased array and gives high-resolution grey scale images of tissues and permits small Doppler sample volumes (0.6 mm × 1.5 mm at 7.5 MHz and 0.9 mm × 2.0 mm at 5.0 MHz) throughout the image. Backscattered signals from red blood cells are displayed in color as a function of their motion toward or away from the transducer (Fig. 1*). The degree of the saturation of the color is used to indicate the relative velocity of the moving red cells, with less color saturation indicating higher velocity (Fig. 2). In addition to the detection of flow data from each pixel in the image, the system also has dual range-gated pulsed Doppler with spectral analysis for display of conventional Doppler data (Fig. 3A).

Real-time color flow mapping devices were first developed and used for cardiac applications.[2–8] This cardiac instrumentation has been described in the literature by a variety of terms, including "color-coded Doppler," "Doppler angiography," "2-D (2 dimensional) Doppler," "Doppler color flow mapping," and "Doppler color flow imaging."[2] These terms tend to be somewhat confusing as they do not allow real distinction among newer methods being developed to allow the simultaneous imaging of tissue and flow. For example, "Doppler color flow mapping" has been used to describe both the frequency

*Color plates I and II appear between pages 592 and 593. Plates III and IV appear between pages 594 and 595. Figures 1–3B appear on Plate I; and Figures 3C–7 appear on Plate II; Figures 8–12 appear on Plate III; and Figures 13–16 appear on plate IV.

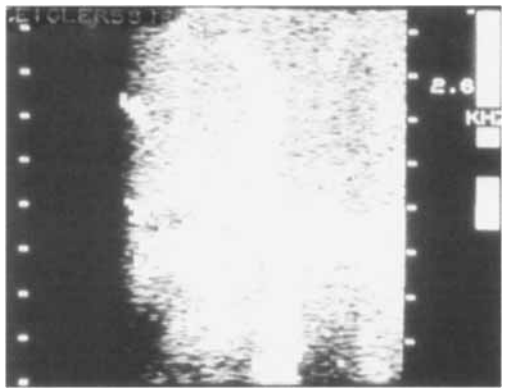

FIGURE 1. Doppler color flow image of the spleen shows the splenic parenchyma in conventional grey scale and the vessels in color flow display. Color indicates direction of flow relative to the transducer. Blood in the splenic arteries is flowing toward the transducer and is shown in red; flow in the splenic veins away from the transducer is shown in blue.

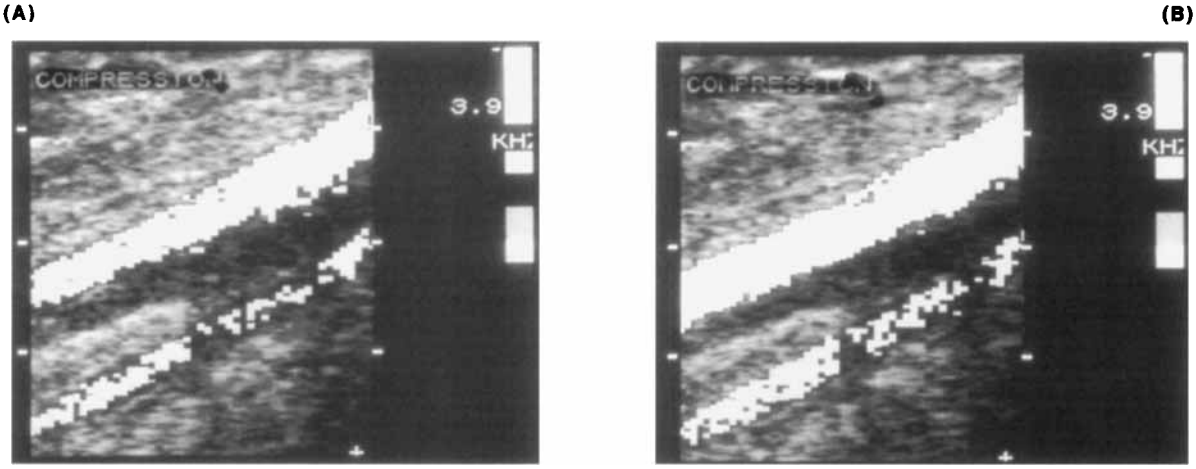

FIGURE 2. With Doppler color flow imaging, color not only indicates direction of flow, but also relative velocity. Highly saturated colors indicate slow velocities; less saturated (lighter) colors indicate higher velocities. **(A)** The superficial and deep femoral arteries are shown in diastole when red cell velocities are relatively slow; this is indicated by the deep saturated color. **(B)** Less saturated colors indicate higher velocities and signal peak systolic flow; also note that the most rapid flow is in the center of the vessel.

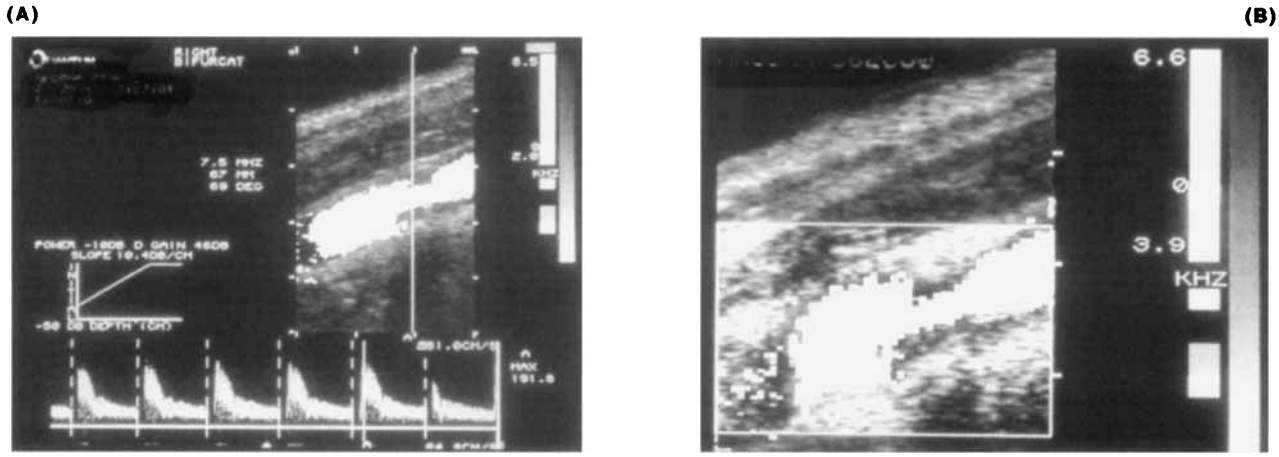

FIGURE 3. In addition to real-time color display of flow data, range-gated pulsed Doppler sampling of Doppler data is possible. Here stenosis of the carotid artery produces a high-velocity jet. **(A)** The velocity spectrum of the sample volume indicated by the cursor is shown. Peak systolic velocities of 191 cm/s confirm severe stenosis. **(B)** The grey scale tissue information has been enhanced by postprocessing to provide improved visualization of the plaque, which has produced the narrowing. Simultaneous visualization of tissue and flow information is a unique advantage of DCFI.

(C)

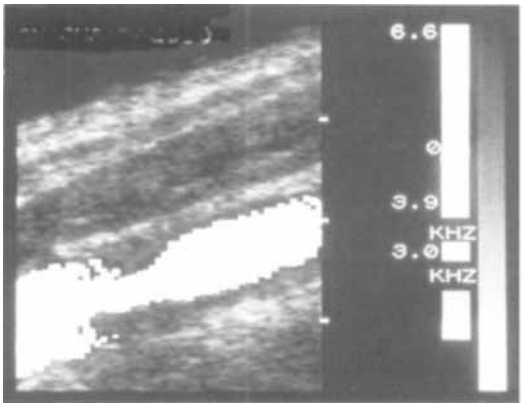

FIGURE 3. (C) Additional postprocessing has been performed to identify areas of flow within the image where Doppler frequency shifts of 3.0 KHz or greater are present. These areas appear in green and are located near the center of the stenotic jet.

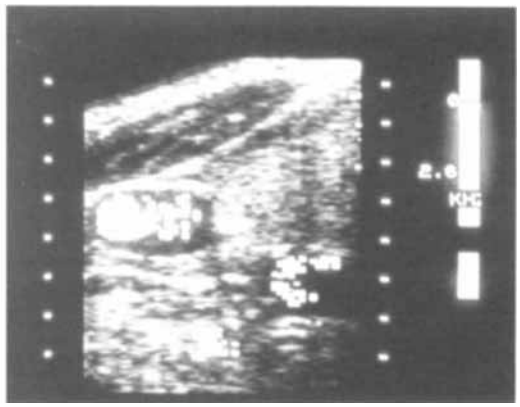

FIGURE 4. A transverse image inferior to the level of the carotid bulb reveals normal flow in the jugular vein (dark blue), and common carotid artery (red). Deep to these vessels the vertebral artery appears light blue. The color in the vertebral artery indicates flow in the direction opposite to that of the carotid artery, allowing diagnosis of reversal of vertebral artery flow associated with the subclavian steal syndrome. High Doppler sensitivity permits imaging of vessels in transverse as well as longitudinal planes, aiding in rapid identification of vessel anatomy and pathology.

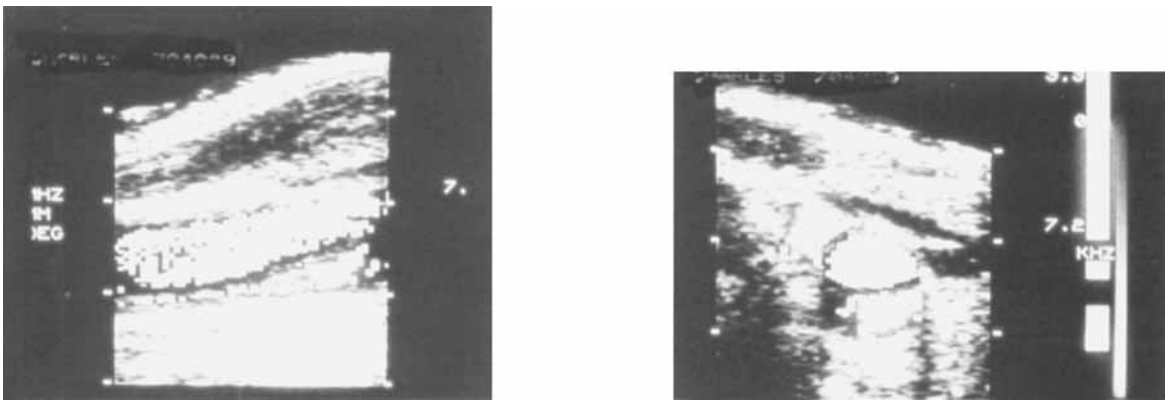

FIGURE 5. Carotid dissection is shown in longitudinal **(A)** and transverse **(B)** planes. Global Doppler sampling permits both the true (red) and false (blue) lumen of the dissection to be identified. In this example the images in diastole (A) and early systole (B) each show reversal of flow in the false lumen.

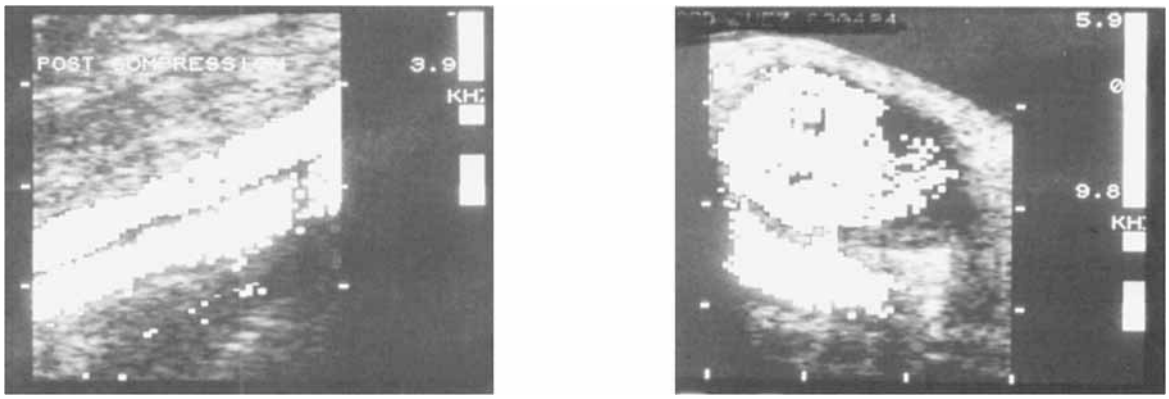

FIGURE 6. Flow in the superficial femoral artery (red) and vein (blue) is shown. Because of the relatively slow velocities in many veins, techniques to improve visualization of venous flow may be necessary. These include alternating compression and relaxation of the vessel, compression of the tissues distal to the vein being imaged, or respiratory maneuvers. In this example, augmented flow in the femoral vein is seen immediately after releasing compression, indicating patency.

FIGURE 7. A large pseudoaneurysm arising from a dialysis fistula shows a turbulent flow pattern. The communication of the pseudoaneurysm with the gortex graft below (blue) is shown very well. In our experience, DCFI has been extremely valuable in the identification of aneurysms, pseudoaneurysms, and other complications of dialysis fistulas.

mapping system, which does not employ real-time imaging, and the cardiac phased array real-time imager.[2,9] A new term, "angiodynography," has recently been introduced to describe the approach developed by Quantum Medical Systems, which allows both flow and tissue information to be collected and viewed simultaneously in real time. Although arguments can be made in support of each of these terms, we prefer "angiodynography" or "Doppler color flow imaging," as these terms allow differentiation of the system we have used from other approaches.

CLINICAL APPLICATIONS

Outside of the cardiac applications of Doppler color flow imaging, the full range of clinical applications of Doppler color flow imaging is only beginning to be explored. Based on our experience, we see three major areas of application of DCFI in addition to the cardiac uses that have been previously described.

1. Primary vascular evaluation. For the carotid bifurcation, aorta, iliac, femoral, popliteal, and other peripheral arteries, applications of DCFI include the detection and measurement of arterial stenosis and flow-restricting or flow-disturbing abnormalities including aneurysm, pseudoaneurysm, and dissection. Assessment of major visceral vessels in the abdomen and pelvis is also possible, along with that of major abdominal, pelvic, and extremity veins for thrombosis or other forms of occlusion.

2. Organ perfusion. Visualization of organ perfusion and inference of end organ changes by display of flow patterns reflecting the state of resistance in the vascular bed supplied by the vessel are important potential applications of DCFI. These uses are especially promising in highly vascular organs such as the native and transplanted kidney, liver, spleen, placenta, and brain.

3. Tumor neovascularity. Color flow imaging may add specificity in the ultrasound examination of masses with display of abnormal vascular patterns associated with tumors. In this application, it is interesting to speculate that the information added to the grey scale tissue display by angiodynography may provide a long-awaited step toward ultrasound tissue characterization.

Our clinical experience with DCFI includes the applications summarized in Table 1. Our impressions of the role of this new form of ultrasound imaging in this range of applications are highly positive. An overview of our experience is provided in the following discussion.

TABLE 1
Clinical Applications of Angiodynography

- Confirmation of presence and direction of flow
- Diagnosis of vascular stenosis or occlusion
- Evaluation of aneurysm, pseudoaneurysm, and dissection
- Recognition of anatomic structures altered by disease
- Portal, hepatic, splenic, and mesenteric vein flow
- Vascular shunt patency
- Tumor vascularity
- Renal blood flow
- Transplant rejection
- Brain blood flow in infants
- Intraoperative imaging

Primary Vascular Evaluation

Carotid bifurcation. The current standard for noninvasive ultrasound imaging of the extracranial carotid and peripheral vessels is provided by duplex Doppler ultrasonography. Modern instruments equipped with 7.5 MHz–10.0 MHz transducers allow high-resolution real-time imaging of the vessel walls, and permit identification and characterization of atheromatous plaque. When coupled with pulsed Doppler systems with variable range gates and spectrum analysis using fast Fourier transformations (FFT), these systems may generate quantitative data relevant to the detection and quantification of flow disturbance. Important limitations of duplex ultrasonography for carotid evaluation are summarized in Table 2. In addition to these general limitations, with carotid duplex ultrasound there may be problems in differentiating high-grade stenosis from total occlusion.[10] Shadowing artifact due to plaque calcification with degradation of the B-mode image and loss of definition of the vessel, and difficulty in maintaining orientation with tortuous vessels, preventing accurate measurement of the Doppler angle and velocity calculation, are also problems in duplex carotid ultrasonography.

With angiodynography, the benefits of conventional duplex sonography are retained and additional capabilities are provided (Table 3). High-quality images of vessel walls and plaques are produced by the 7.5-MHz transducer used for im-

TABLE 2
Limitations of Conventional Doppler Ultrasound Imaging

- Sampling problems
- Competing design factors
- Aliasing
- Complex Doppler data
- Information not intuitive
- Technical skill requirements
- Length of examination

TABLE 3
Advantages of Doppler Color Flow Imaging

- Simultaneous real-time Doppler and tissue information
- Global Doppler sampling
- Identification of turbulence and high-velocity jets that might be missed due to sampling error with duplex sonography
- Ease of Doppler angle measurement
- Improved contrast between vessel wall and the lumen, allowing better estimation of residual lumen, plaque surface, etc.
- Rapid acquisition of data, allowing for faster examination

aging, an important consideration for plaque characterization (Fig. 3B).[11] Range-gated pulsed Doppler with FFT spectral analysis is available for quantitative measurements. The use of color saturation to display variations in Doppler shift frequency allows a semiquantitative estimate of flow to be made from the image alone. The color display of flow throughout the image field allows the position and orientation of the vessel of interest to be observed at all times. Because of the small volumes from which Doppler information is sampled, the image displays the spatial distribution of velocities within the lumen of a vessel, with higher velocities in the center and slower velocities along the vessel wall (Fig. 2B). The ability of angiodynography to provide this spatial information with respect to velocity makes angiodynography an ideal method to display small localized areas of turbulence within a vessel; this in turn often provides a clue to stenosis or irregularity of the vessel wall caused by atheroma, trauma, or other disease.

Since flow within the vessel is observed at all points, stenotic jets and focal areas of turbulence are immediately seen, where with conventional pulsed Doppler incomplete sampling might result in these areas being overlooked. The contrast of flow within the vessel lumen enhances the visibility of wall irregularities and plaques, which are not always seen well with conventional instrumentation (Fig. 3B). Postprocessing allows measurement of peak frequency from the image without the necessity of time-consuming gated samplings (Fig. 3C). Finally, high sensitivity, even at small Doppler angles, allows visualization of flow in transverse planes, aiding in vessel identification and measurement of lumen area (Fig. 4). These features result in a reduction in the time required for most carotid examinations. Although we have not completed a systematic study to compare the accuracy of DCFI with duplex methods, our subjective impression based on the comparison of angiodynography and duplex ultrasound in over 150 carotid evaluations is that DCFI is more accurate and allows a more confident diagnosis of both normal and abnormal vessels. The excellent flow sensitivity of Doppler color flow imaging suggests that the incidence of false positive diagnosis of complete occlusion may be less than with duplex systems.

Other vascular applications. Depending on patient size and the amount of superimposed gas, the aorta, inferior vena cava, and iliac arteries and veins may be studied for changes that include occlusion, narrowing, dissection, and aneurysm. In essentially all patients, flow within the femoral and popliteal arteries and veins can be studied. The evaluation of vascular dissection (Fig. 5), aneurysms, and pseudoaneurysms is performed quickly and accurately with angiodynography, and is now being used in lieu of angiography in selected patients. Because flow in the femoral, saphenous, and popliteal veins may be relatively slow, augmentation methods to improve flow detection are used (Fig. 6). Excellent access and visualization of dialysis fistulas for thrombosis, stenosis, and pseudoaneurysm are resulting in excellent clinical acceptance of DCFI as the initial diagnostic examination when these complications are expected (Fig. 7).

Organ Perfusion

Changes in tissue function are often associated with changes in blood flow. Early duplex Doppler systems designed for cardiac and peripheral vascular applications were limited in their ability to detect tissue flow, but newer systems with improved sensitivity now allow duplex scanning of abdominal and pelvic organs, permitting access to tissue information. Taylor and Burns have reported that semiquantitative analysis of the Doppler shift frequency with time can be used to infer both proximal stenosis and changes in distal vascular impedance.[1] Using pulsed Doppler, several investigators have shown that pathological changes in various organs and tissues, including the kidney,[1,12] renal transplant,[1] breast,[13–16] and liver,[1] are reflected in changes in arterial flow patterns. At this time, we believe DCFI has similar potential for inference of flow at the parenchymal level in the liver, kidney, spleen, placenta, and brain. Some of our specific observations are summarized in the following paragraphs:

Liver. We have used angiodynography successfully to visualize normal hepatic, portal, mesenteric, and splenic arterial and venous flow (Figs. 1 and 8), and to characterize hepatic abnormalities. Doppler color flow imaging has been helpful in the confirmation of portal vein throm-

FIGURE 8. A transverse view of the liver reveals flow within hepatic and portal veins. That some hepatic veins appear blue and others red is related to the direction of flow relative to the transducer, with flow toward the transducer shown in red.

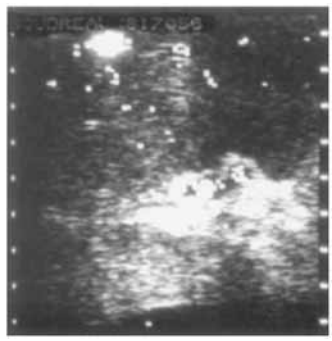

FIGURE 9. Collateral veins (red) are seen in the porta hepatis of a patient with portal vein thrombosis. DCFI has been useful in evaluation of portal vein patency and flow direction, and has been sensitive in identifying portosystemic collaterals in patients with portal hypertension.

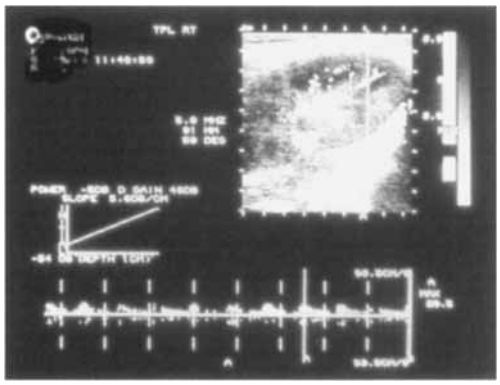

FIGURE 10. Color flow image of a normal renal transplant shows flow in the interlobar, segmental, and main renal arteries. With DCFI, the ability to image small vessels allows precise measurement of the Doppler angle, allowing accurate velocity measurements, as indicated in the sampling of the interlobar vessel in this patient.

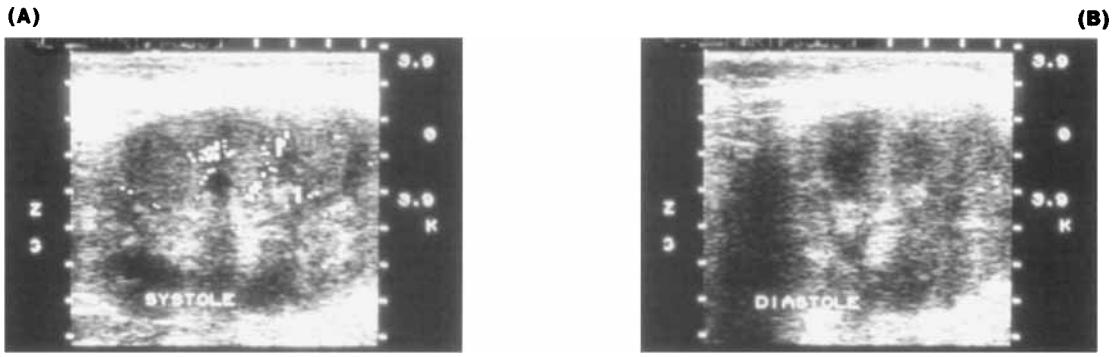

FIGURE 11. Vascular changes accompanying acute rejection of the renal transplant are shown in systolic **(A)** and diastolic **(B)** color flow images. In the normal kidney, the low resistance of the renal vascular bed results in forward flow in the intrarenal arteries throughout diastole. In this patient with acute rejection, there is reduced arterial flow in systole and absent flow in diastole.

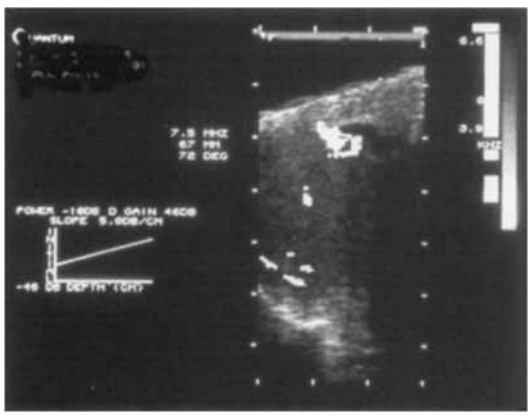

FIGURE 12. Abnormal vessels are seen along the margins of a solid testicular mass. Biopsy confirmed the diagnosis of seminoma. With DCFI we have observed abnormal vascular patterns associated with malignant tumors in numerous sites, including the liver, kidney, testicle, breast, brain, thyroid, and soft tissues.

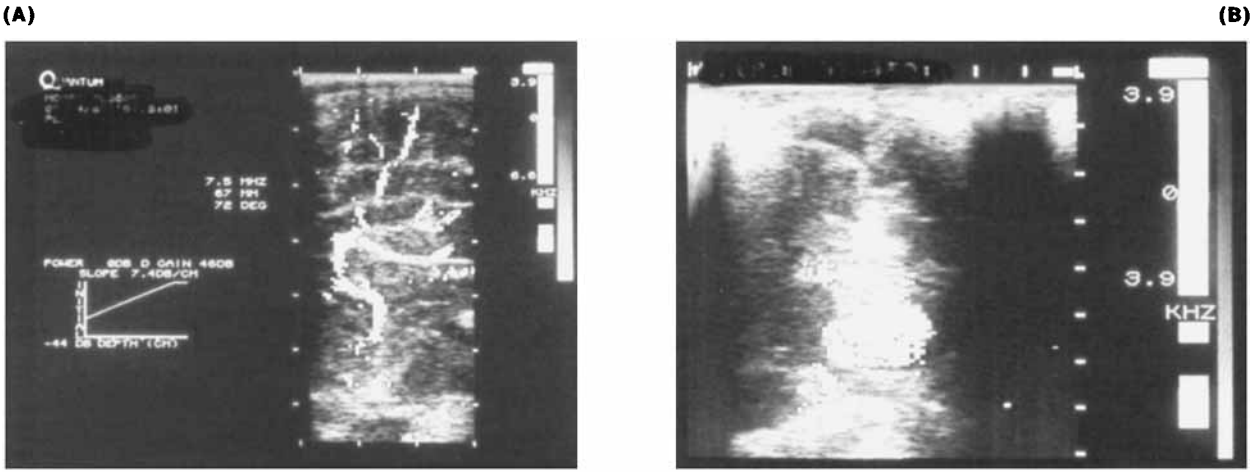

FIGURE 13. Intracranial blood flow is in an image obtained through the anterior fontanelle in a newborn infant. The sagittal view **(A)** shows the internal carotid, the anterior cerebral, and cortical branches of the anterior cerebral artery.
The coronal image **(B)** shows turbulent flow within a vein of Galen aneurysm. Portions of two large feeding vessels are seen along the left side of the image.

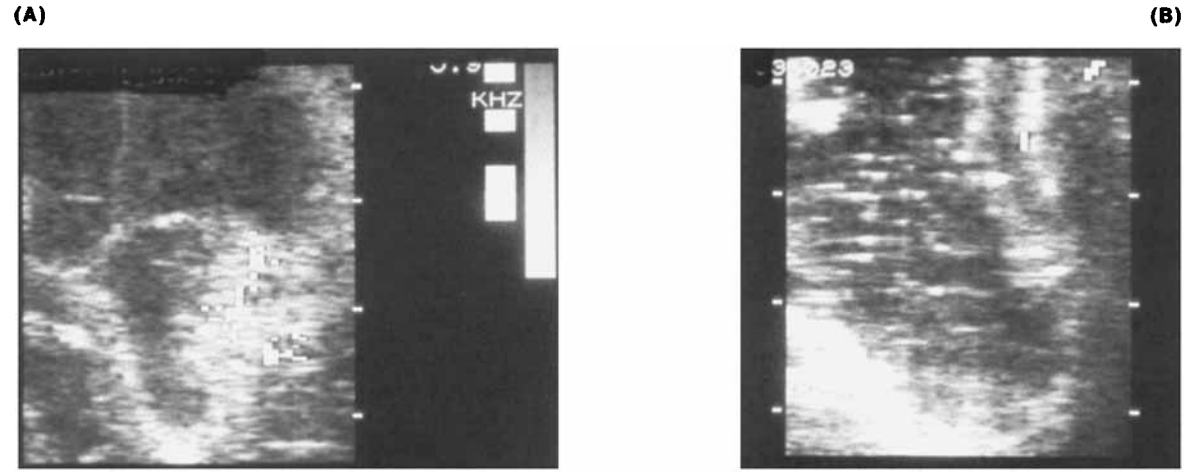

FIGURE 14. An intraoperative scan of a 1.5-cm cerebral arteriovenous malformation (AVM) is shown before **(A)** and after **(B)** resection. **(A)** The hypoechoic area adjacent to the vascular lesion represents a large intracerebral hematoma. With DCFI, the AVM is easily distinguished from adjacent normal brain tissue by the demonstration of its abnormal vascularity.
After resection, scanning **(B)** shows absence of the abnormal vessels, confirming complete resection.

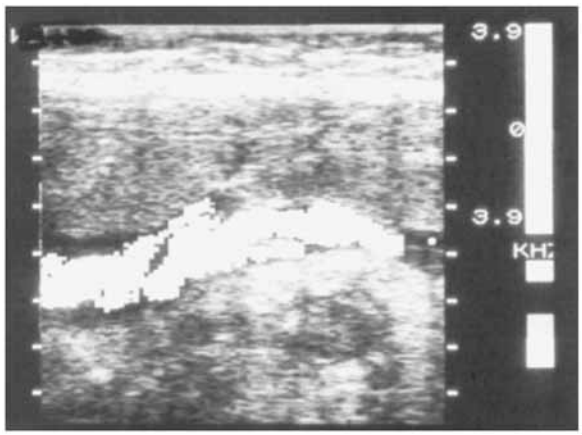

FIGURE 15. Normal flow in umbilical arteries (red) and vein (blue) is seen in a third trimester pregnancy. With DCFI placental, uterine, and fetal blood may be imaged. Obstetrical applications of DCFI are only beginning to be explored, but hold considerable potential.

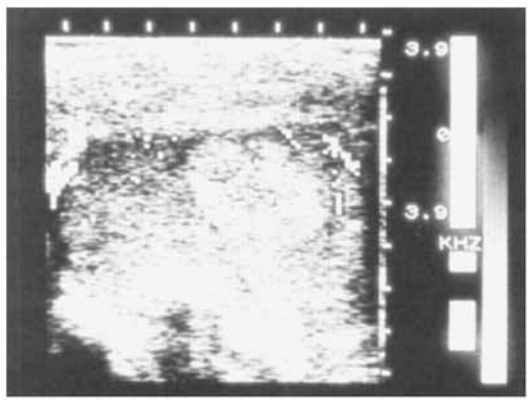

FIGURE 16. Tumor vascularity is seen in the liver of a patient with hepatoblastoma. Abnormal vessels are seen at the periphery of the tumor. Increased vessel number, irregular vessel course and caliber, and high velocities are common features of tumor vascularity seen with DCFI.

bosis and may demonstrate collateral recanalization as well as changes in hepatic artery flow that accompany this pathology. Also, portosystemic collateral vessels in patients with portal hypertension are readily detected (Fig. 9).

Kidney. Normal renal arteries and veins are often imaged, allowing potential application of DCFI in the evaluation of renal vessel stenosis and occlusion. In many patients, intrarenal vessels, including segmental, interlobar, and arcuate vessels, are visible, and diminished patterns of flow in these vessels have been observed in patients with renal parenchymal disease. The future role of DCFI in the evaluation of renal perfusion remains to be defined, but the capabilities provided by new imaging methods are promising.

Transplants. Transplant dysfunction may result from vessel stenosis, occlusion, or parenchymal changes secondary to rejection, tubular necrosis, or drug toxicity. The ability of DCFI to image not only major vessels for primary abnormalities, but also the dynamics of flow that reflect perfusion, encourages investigation of routine postoperative assessment of hepatic and renal transplants. Because of the superficial location of the transplanted kidney, excellent detail of intrarenal and extrarenal vessels is obtained with DCFI (Fig. 10). Significant differences in perfusion patterns have been observed in patients with rejection and acute tubular necrosis, resulting in a visual analogue of the pulsatility index (Fig. 11).[17]

Other applications: thyroid, testicle, breast, brain, intraoperative, and obstetrical. We have used DCFI in the evaluation of blood flow to the thyroid, testicle, breast, and brain. High Doppler sensitivity permits normal vessels supplying the thyroid and testicle to be imaged. In the testicle, abnormal flow patterns have been seen with varicocele, torsion, and malignant tumors (Fig. 12). In neonates, cerebral perfusion is clearly seen using access provided by the open fontanelle (Fig. 13). Similar useful information related to brain flow can be obtained with intraoperative DCFI, and we have found this application to be particularly helpful in the intraoperative monitoring of resection of cerebral arteriovenous malformations (Fig. 14). Other intraoperative applications that appear promising include the inspection of vessels following endarterectomy.

Applications of DCFI in obstetrics are only beginning to be explored (Fig. 15). Imaging of uterine, placental, umbilical cord, and fetal vessels throughout pregnancy is possible. The addition to color flow imaging to conventional Doppler methods may allow improved understanding of a wide range of maternal and fetal problems.

Tumor Vascularity

Vascular changes associated with malignant tumors may be demonstrated by Doppler ultrasound. A number of reports in the literature have described characteristic signal patterns from malignant tumors using both continuous wave and pulsed Doppler.[1,13–16] The patterns that have been described generally involve the periphery of the tumor, and include a characteristic Doppler spectrum with relatively high peak systolic velocities and a predominance of high-power, low-frequency elements. We have been interested in the ability of angiodynography to demonstrate vascular changes in tumors, and have evaluated patients with tumors of the liver, kidney, breast, thyroid, and soft tissues. In the liver, most metastatic lesions have shown evidence of increased vascularity (Fig. 16). Increased vascularity has also been seen at the periphery of a number of tumors of the breast, testicle, thyroid, parathyroid, and soft tissues. If these vascular changes are relatively specific for malignant tumors, it is tempting to speculate that sonographic methods for detection of tumor neovascularity may add to the specificity of tumor diagnosis. Angiodynography and associated developments in Doppler techniques may thus result in an increased future role for ultrasonography in the characterization of malignant tumors.

DISCUSSION

There are significant differences between conventional duplex Doppler imaging and DCFI. Although duplex instrumentation has been the most widely accepted method for vascular applications, its disadvantages have slowed the acceptance of this method.[18] Among these limitations, the most important are the following:

1. Sampling problems. Flow data are obtained only from a small sample, and precise positioning of the Doppler sample volume is required to obtain accurate measurements. With both pulsed and continuous Doppler techniques at any point and time, frequency shifts can be detected only along the one-dimensional path of the ultrasound beam. A major implication of this sampling problem is that, in cases where flow disturbances are isolated to relatively small areas (as is commonly the case), the abnormality may be missed due to failure to position the sample in

the small region where the stenotic jet or turbulence is present. With pulsed Doppler, sampling error may therefore result in localized areas of severely disturbed flow being missed or underestimated.

2. *Technical skill requirements.* Complex Doppler data and the need for accurate sampling make the duplex ultrasound examination one of the most technically demanding ultrasound procedures performed in most departments. The special training and skills required to be proficient in this technique have undoubtedly slowed the acceptance of Doppler ultrasound.

3. *Examination time.* To be confident that a conventional range-gated Doppler study has achieved reasonable sensitivity and specificity in detection of flow disturbances, a methodical and frequently time-consuming search and sampling must be performed. As a result, duplex studies are often lengthy examinations to perform, especially when difficult vascular anatomy or advanced disease creates complex scanning situations.

4. *The information is complex and not intuitive.* Since the Doppler signal itself has no anatomic significance, the examiner must interpret the Doppler signal and then determine its relevance in the context of the image. Components of the Doppler data that must be evaluated include the Doppler shift frequency and amplitude, the spatial distribution of frequency across the vessel, and the temporal variation of the signal. The complexity of the Doppler data has also influenced the rate of acceptance of Doppler by specialists who are accustomed to anatomically referenced images. This problem has been partially addressed by Doppler mapping devices that present a map of the Doppler shift frequencies in a color-coded display.[9] These systems, however, suffer the limitations that real-time imaging is not possible and that B-mode tissue information is not displayed, preventing such important imaging objectives as plaque characterization.

With DCFI, many of the limitations of duplex Doppler instrumentation are overcome. Some of the specific features of DCFI that we have found to be most important in this regard are as follows:

1. *Global Doppler sampling.* The need to place the sample volume in a specific location for quanitative analysis is obviated since the Doppler flow parameters (i.e., mean Doppler frequency shift) for each pixel in the entire B-mode image is displayed in real time.

2. *Ease of measurement of Doppler angle.* When using Doppler methods, the accurate estimation of velocity requires correct measurement of the angle of the sound beam with respect to the axis of flow. With conventional scanners, this may be difficult if the vessel is small or cannot be seen well. With angiodynography, the display of the presence of flow permits even small vessels to be seen with ease, allowing precise determination of the direction of flow and thus the Doppler angle.

3. *Simultaneous real-time Doppler and tissue information.* With angiodynography, the Doppler frequency in each pixel is updated in each real-time frame (up to 18 frames per second or greater). Where there is significant vessel motion, this is a significant benefit over duplex systems in which the tissue image is usually either frozen or updated at a relatively slow rate.

4. *Ease of operation.* Since flow information is contained in the image and sampling is not necessary, we have found that less training is required to allow basic flow data to be collected than with conventional Doppler instrumentation.

CONCLUSIONS

To date, our experience with Doppler color flow imaging in over 500 examinations has given us a positive impression of this new method of ultrasound imaging. The disadvantages and limitations of the system are few. In the abdomen, gas produces a severe color artifact due to the phase and frequency changes induced by the markedly reduced velocity of sound in air. Scanning of areas containing much gas is more difficult than with conventional ultrasound. The complex technology required to produce a real-time instrument with an effective combination of flow and tissue imaging understandably carries a high price tag, which we feel is justified by the unique capabilities of the instrumentation.

The ability to image vascular flow and tissue characteristics simultaneously permits simple, rapid, and accurate evaluation of large vessels for stenosis, occlusion, and flow disturbance. Most significant abnormalities can be detected from the image alone, but quantitative measurement of flow characteristics is also possible. In addition, we believe the technique shows great promise for the evaluation of the vascular supply of abdominal and pelvic organs, and for obtaining clinically useful information related to organ perfusion and tumor neovascularity. With DCFI, we may finally begin to see some useful degree of ultrasound tissue characterization based on tissue perfusion patterns.

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