Influence of the Coanda Effect on Color Doppler Jet Area and Color Encoding

In Vitro Studies Using Color Doppler Flow Mapping

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We studied surface adherence and its effects on color Doppler jet areas and color encoding in an in vitro model with a noncompliant receiving chamber into which a steady flow jet was directed parallel to either a straight or a curved surface adjacent to and 4 mm away from the inflow orifice (1.50 mm^2) with the control condition being a free jet matched for flow rates and driving pressures. Jets were imaged perpendicular to the plane of the surface, the plane in which most clinical images of jet–surface interactions are obtained. Ten different flow rates ranging from 0.13 to 0.30 l/min were used. Surface-adherent jet areas were smaller than control jets for every driving pressure–volume combination (paired *t* test, $p<0.01$). Computer analysis of color Doppler images showed more green and blue (reverse flow) pixels on the surface side of the adherent jets than the control jets ($p<0.05$), suggesting that viscous energy loss and flow deceleration and reversal play a role in the jet–surface interaction. Analysis of variance demonstrated that linear regression slopes of flow rate versus jet area for surface jets were lower (slopes, 11–21 cm^2/l/min; $r=0.95$–0.97) than those for the control (slope, 33 cm^2/l/min; $r=0.97$) ($p<0.0001$). Surface adherence (Coanda effect) influences jet size and color encoding, causing smaller color Doppler jet areas and greater variance and reverse velocity encoding. (*Circulation* 1992;85:333–341)

Color Doppler echocardiography has become an important and widely used diagnostic technique for definition of intracardiac blood flow patterns, especially in valvular heart disease. Efforts by investigators have recently been directed to relating information from echo Doppler and color flow mapping studies to hemodynamics, blood flow volume, and flow physics to aid development of more rational and quantitative methods for applying this technology. A number of previous studies have attempted to quantitate regurgitant jet flow area by color Doppler flow mapping as an estimate of the clinical severity of both mitral and aortic regurgitation.[1,2] Many factors, however, have been demonstrated to influence the jet area in color Doppler flow mapping, such as instrument settings (pulse repetition frequency, frame rate, color gain, and Nyquist limit) and "physiological" variables (receiving chamber size, chamber compliance, regurgitant orifice diameter, and driving pressure of regurgitation).[3–11] Different color Doppler systems used on the same patient may also produce a variety of jet areas.[8,12] Recently, it has been noted that eccentric regurgitant jets flowing close to the atrial wall or the ventricular septum appear smaller on color Doppler than unbounded jets issuing into the center of the ventricle or atrium.[13]

The Coanda effect is a hydrodynamic phenomenon describing the surface adherence of jets wherein a jet flow near a surface results in asymmetric expansion of the jet because of reduced mass entrainment on the side of the jet close to the surface.[14] Increased shearing forces caused by higher spatial velocity differentials in the transverse direction cause the jet stream to deviate toward and adhere to the surface, keeping the jet stream from expanding farther downstream on the affected side.[15,16] Jet growth by entrainment can proceed only on the side opposite the surface. Intracardiac surfaces such as the ventricular septum, the mitral leaflets, and the left atrial wall adjacent to an eccentric aortic insufficiency or mitral

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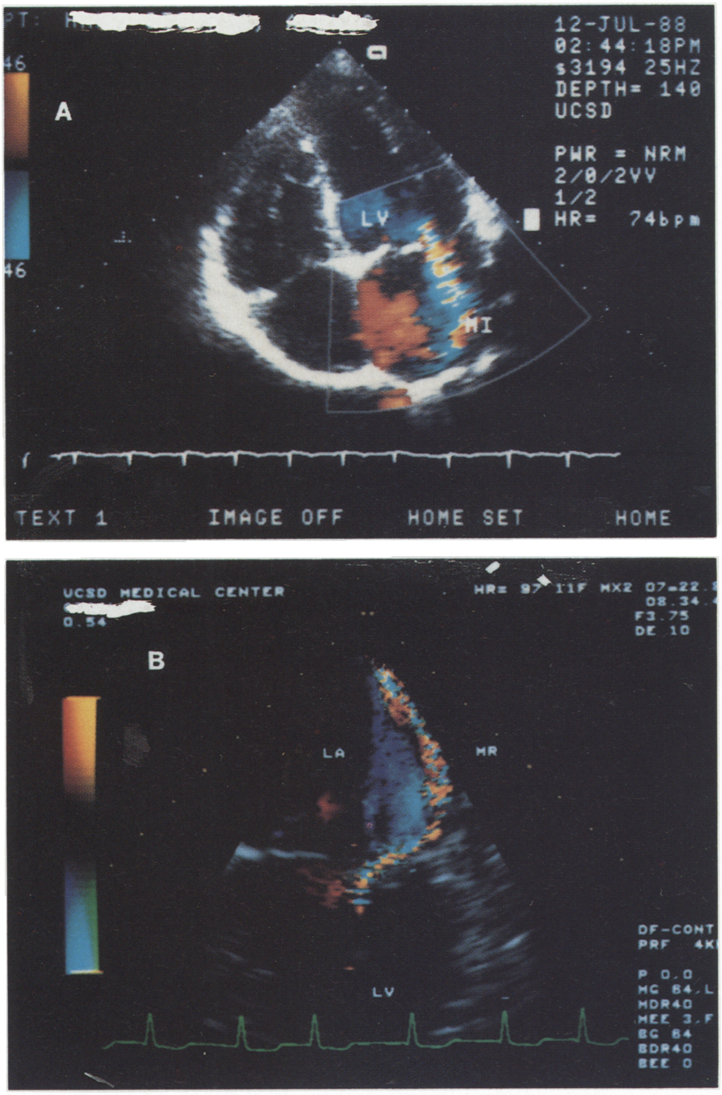

FIGURE 1. *Color Doppler image showing an in vivo example of jet deviation and adherence to a physiological surface.* Panel A: *Apical four-chamber view of a patient with mitral insufficiency (MI) and a free regurgitant jet that enlarges in width symmetrically by entrainment as it penetrates the left atrium. LV, left ventricle.* Panel B: *Transesophageal view demonstrating deviation of mosaic patterned MI regurgitant jet first adhering along the posterior surface of the posterior mitral leaflet and then in the left atrium (LA) as it hugs the left atrial wall. Note that the jet remains quite narrow.*

regurgitation jet can potentially produce a Coanda-like effect. The unique hydrodynamics associated with surface-adherent jets may affect how a color Doppler scanner computes and displays the information obtained from such flows and therefore influence the quantification and color encoding of valvular regurgitation by color Doppler in certain patients (Figure 1). Because two-dimensional color jet size is still used as a qualitative measure of valvular disease severity and because computer off-line pixel analysis of color Doppler images to calculate momentum, kinetic energy, variance, and so on is increasing in popularity, we modeled the Coanda effect in vitro to evaluate the influence of an adjacent surface on both regurgitant jet size and Doppler color pixel encoding.

Methods

In Vitro Model

The model consisted of a noncompliant receiving chamber: a 10×10×4-cm rigid plastic box with 1.5-mm^2 cross-sectional area inflow orifice and an unrestrictive outflow orifice. A continuous-flow pump was connected to both orifices to make a closed circuit. The model was filled with a 0.2% (by weight) cornstarch-in-water suspension to produce physiological ultrasound reflections. A window for the echo transducer was constructed on the side opposite the inflow orifice so that jets were imaged going toward the transducer. One of a family of smooth aluminum surfaces was inserted alongside the inflow orifice adjacent to or 4 mm away from the side of the inlet orifice. The surfaces were 6 cm in length along the direction of flow and 2 cm wide and were modeled in two shapes: one straight and the other curved and convex away from the jet. We chose not to use a concave surface, which would naturally confine the jet by intercepting its trajectory, an impingement effect resulting in flow hydrodynamics that are different from the physics for a surface-adherent flow and would not allow separate determination of surface adherence per se. Although many physiological surfaces are concave to flow, instances also exist where the flow stream encounters a convex surface, such as in mitral regurgitation, where the jet stream may

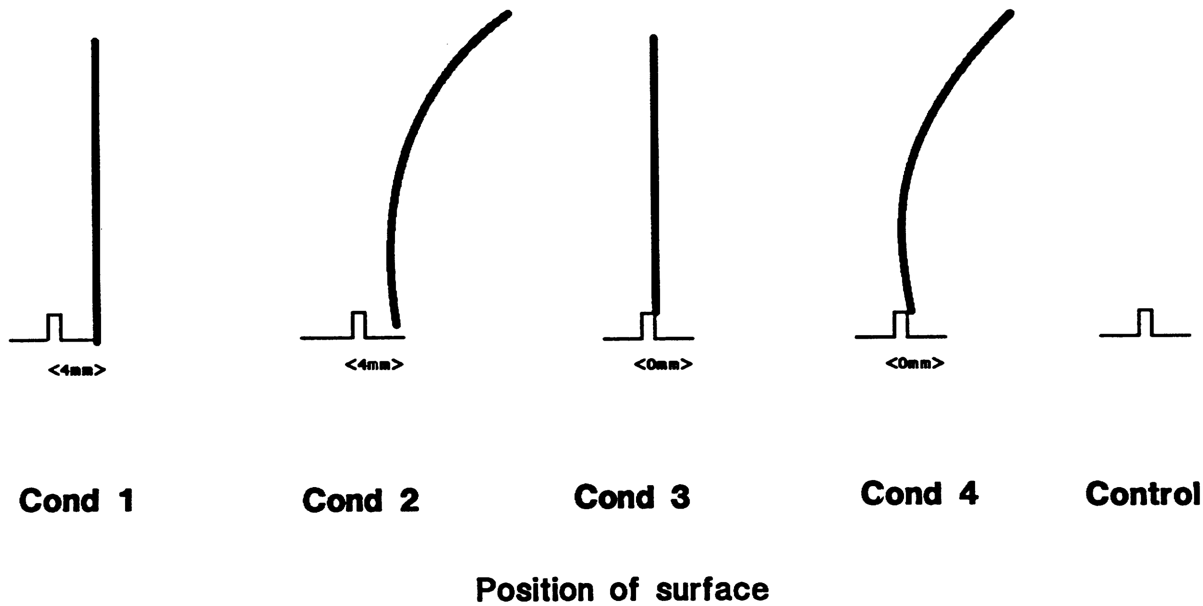

FIGURE 2. *Graphs of curved and straight lines stand for the surfaces: curved and straight. The surface was placed almost 0 mm (conditions 3 and 4) and 4 mm (conditions 1 and 2) away from the inflow orifice. An identical model with the same chamber and flow rate but without the surface was used as the control condition.*

adhere to the back of the mitral valve and travel along the atrial septum. In order to evaluate surface effects on jet size, we combined the two different surface shapes and two different distances at which the surface was offset to the side of the orifice (Figure 2): condition 1, a straight surface offset 4 mm to the side of the inflow orifice; condition 2, a smoothly curved surface convex to the jet and offset 4 mm away; condition 3, a straight surface placed adjacent to the origin of the jet; and condition 4, a smoothly curved surface also adjacent to the origin of the jet. A control condition without the surface (free jet) was used as the fifth condition.

Flow rates were calculated by measuring flow velocity by continuous-wave Doppler (in centimeters per second) combined with the known cross-sectional area of the inflow orifice (in square centimeters) and were cross-checked against measurements using a stopwatch and graduated cylinder to ensure that vena contracta effects were minimal. Ten different continuous flow rates ranging from 0.13 to 0.30 l/min were studied in this model with jet velocities from 1.44 to 3.78 m/sec and Reynolds numbers from 1990 to 5225.

Two-dimensional Color Flow Mapping Study

For imaging the flow jets, we used a Toshiba SSH65A color Doppler scanner with a 3.75-MHz phased array transducer placed on the window opposite the inflow orifice. The echo sector was aimed at the inflow orifice to image the central plane of the flow jet and to optimize jet size in the plane perpendicular to the jet surface, because this is the most common clinical echo plane in which these interactions are observed (Figure 1). Images were obtained at a color gain setting just below that which produced noise in the color Doppler image, and this setting was kept constant throughout the study. A fixed pulse repetition frequency of 4 kHz was used, yielding a Nyquist limit of 0.54 m/sec. Images were recorded on a ¾-in. videotape for further analysis.

Data Measurements

Resultant jet flow areas (Figure 3) and color encoding were measured with a Sony RGB color analyzing computer with appropriate software for planimetry. Jet area values were expressed as mean±SD (in square centimeters), and flow rates were expressed in liters per minute. Four frames from each flow rate in each condition were measured and averaged for jet size. For jet area measurement, we chose those frames with the largest color Doppler jet area as imaged in the velocity-variance mode. None of the jet images showed color overlap beyond the ultrasound scan sector, and jet area was defined as all contiguous color within the ultrasound sector. To determine how the ultrasound system computed the relative flow changes on the surface side of the surface-adherent jets as opposed to the same side for the free jets, selected imaged frames and the jet areas defined within them were digitized, and a histogram analysis was performed on the blue, red, and green pixels for the two sides of each jet. Each horizontal row of pixels corresponding to the intensities of the red, green, and blue components was divided along a line determined from the image to be the center of the jet for both curved and free jets, and the number of pixels and the intensities of each color component were measured for each side. This was performed for the entire length of the jet, and the numbers were averaged to provide mean red, green, and blue

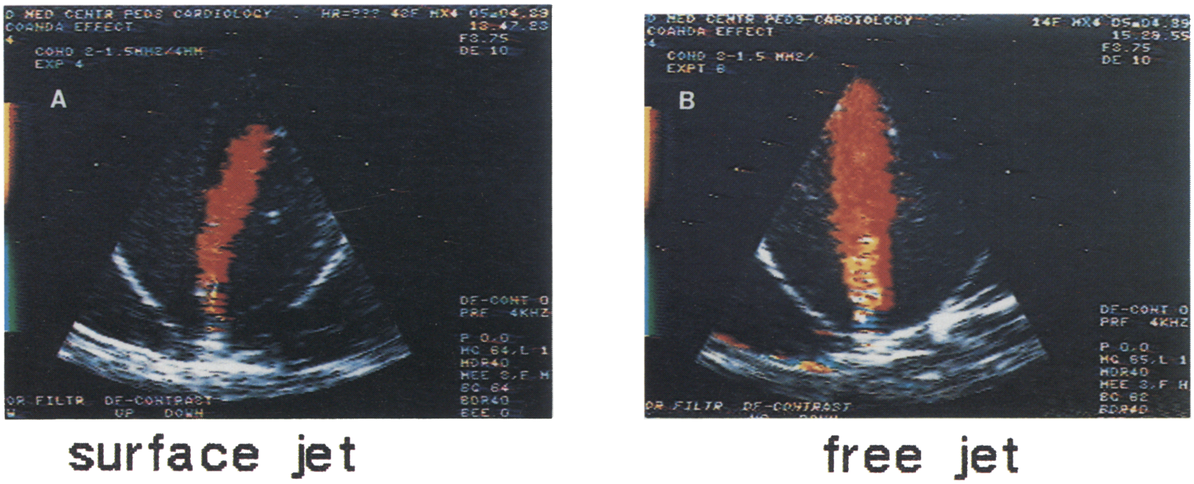

FIGURE 3. *Color Doppler image showing how an adjacent surface reduces color Doppler jet areas.* Panel A *is an example from condition 4, where a curved surface was placed adjacent to (0 mm from) and to the right of the jet orifice. Note that compared with the control condition, that is, a free jet at identical flow rate, orifice size, and machine settings* (panel B), *the surface jet area is much smaller.*

intensities and mean pixel numbers for each color on either side of the jet's centerline axis. Data were also analyzed for the entire identified area of free jets and surface jets for histogram analysis of blue, red, and green pixels. This general histogram analysis has been described previously.[17,18]

Interobserver and Intraobserver Variability

Images were reviewed frame by frame by one observer on two different occasions (intraobserver variability). A second observer independently performed the same measurements at another time (interobserver variability). The two observers were blinded to each other's results.

Data Analysis

Flow rates and jet flow areas were correlated by simple linear regression analysis. One-way analysis of variance (ANOVA) and regular paired and Bonferroni t tests were used for the statistical analysis. The free jet condition was used as the control against which the other conditions were compared. A value of $p<0.05$ was considered statistically significant.

Results

For 10 flow rates ranging from 0.13 to 0.30 l/min, the corresponding jet areas, correlation coefficients, linear regression relations, and ANOVA and t test results for each experimental condition are illustrated in Table 1 and Figure 4.

Relation of Jet Area to Flow Rate—Regression Analysis

For each condition relating to the position of the surface in the receiving chamber, jet area showed an excellent correlation with flow rate, as has been shown

TABLE 1. **Results of Jet Area Measurements**

Flow rate (l/min)	Condition 1 (cm^2)	Condition 2 (cm^2)	Condition 3 (cm^2)	Condition 4 (cm^2)	Control (cm^2)	Analysis of variance
0.13	2.51±0.15	2.70±0.12	2.37±0.16	1.42±0.13	3.42±0.04	$p<0.0001$
0.15	3.31±0.22	3.29±0.13	2.81±0.18	2.26±0.06	3.27±0.13	$p<0.0001$
0.17	3.19±0.12	4.00±0.16	2.97±0.21	2.23±0.13	4.26±0.05	$p<0.0001$
0.18	3.65±0.24	4.51±0.35	2.65±0.30	2.50±0.33	4.65±0.07	$p<0.0001$
0.20	3.86±0.26	4.27±0.34	3.04±0.11	2.45±0.08	5.17±0.17	$p<0.0001$
0.21	4.34±0.08	4.67±0.23	3.38±0.10	3.26±0.28	5.13±0.10	$p<0.0001$
0.22	4.26±0.13	4.51±0.18	3.11±0.11	3.85±0.09	6.02±0.12	$p<0.0001$
0.24	4.42±0.15	4.76±0.26	3.72±0.11	3.82±0.13	7.58±0.27	$p<0.0001$
0.28	4.90±0.09	6.20±0.15	3.89±0.08	4.66±0.27	7.99±0.11	$p<0.0001$
0.30	5.30±0.17	6.36±0.15	4.47±0.19	5.17±0.16	8.17±0.26	$p<0.0001$
	$p=0.001$	$p=0.001$	$p=0.006$	$p=0.002$		
	$r=0.97$	$r=0.97$	$r=0.95$	$r=0.97$	$r=0.97$	
	$n=10$	$n=10$	$n=10$	$n=10$	$n=10$	

Values are mean±SD.
Probability values from paired t test; a value of $p<0.05$ was considered significant.
Regression values are comparisons of jet area vs. flow rate.

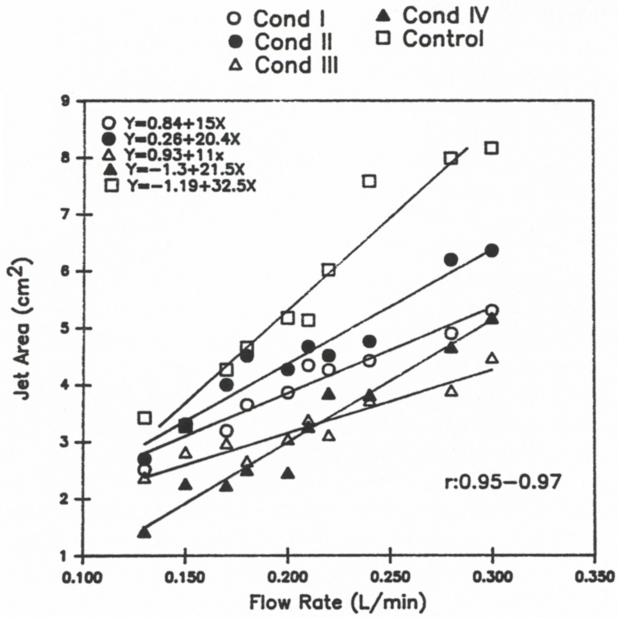

FIGURE 4. *Graph showing the relation between flow rate and jet area for each condition; correlation coefficients for each condition ranged from 0.95 to 0.97. The control condition has the highest slope of all the conditions. In conditions 1 and 2, the surface was placed 4 mm away from the inflow orifice, resulting in a larger jet area than conditions 3 and 4, in which the surface was placed adjacent to the inflow orifice.*

in most in vitro studies where all other conditions are constant (r=0.95–0.97) (Figure 4). The control condition (jet flow without a surface) had the largest jet area for each flow rate and the highest slope (33 cm^2/l/min) for the relation between jet area and flow rate (ANOVA, $p<0.0001$). *t* Test analysis showed that the linear regression relations between jet area and flow rate for conditions 2 and 4 (curved surface) had higher slopes, 20 and 21 cm^2/l/min, respectively ($p<0.0001$) than the slopes for conditions 1 and 3 (straight surface) (15 and 11 cm^2/l/min, respectively).

Comparison of Jet Area at Each Flow Rate for Surface Jets Compared With Control Jets

Paired *t* tests showed that the control flow jet area was larger than the jet area of each surface condition at each flow rate ($p<0.01$) (Figure 3). Those conditions with the surface adjacent to the inflow orifice either with straight (condition 3) or with curved shape (condition 4) showed jets with smaller areas for the same flow rates than the corresponding conditions (1 and 2) with the surface placed 4 mm away ($p<0.05$).

Comparison of Color Encoding

Our observations on color encoding demonstrated that the surface does affect the color Doppler imaging of the jets. We consistently observed a greater number of blue and green pixels on the surface side of the jet. For the surface jets, when the surface side of each jet was compared with the free side of the same jet, the number of blue pixels as a percentage of total pixels (4.8±0.03% [mean±SD]) and the number of green pixels as a percentage of total pixels (30.8±11%) were higher on the surface side than on the free side, although the values for percent green intensity were not statistically significant (1.8±0.02% for blue, p=0.017; 24.0±0.09% for green, p=NS). When free jets were compared with surface jets, the percentages of blue and green pixels on the surface side of the surface jets, 4.8±0.03% for blue and 31±11% for green, were significantly higher than the percentages of blue and green pixels on the same side of the free jets, 1.3±0.7% blue and 20.9±4% green, respectively, both $p<0.05$ using flow rate as the pairing factor (Figure 5). Data for the whole jet area, not divided into segments, including complete pixel counts for paired free jet and surface jets, showed 1.9±0.02% blue pixels and 21.3±0.09% green pixels in free jets compared with 3.6±0.03% blue pixels and 34±0.9% green pixels in the surface jets at the same flow rate, both $p\leq0.05$. As such, the surface jets as a

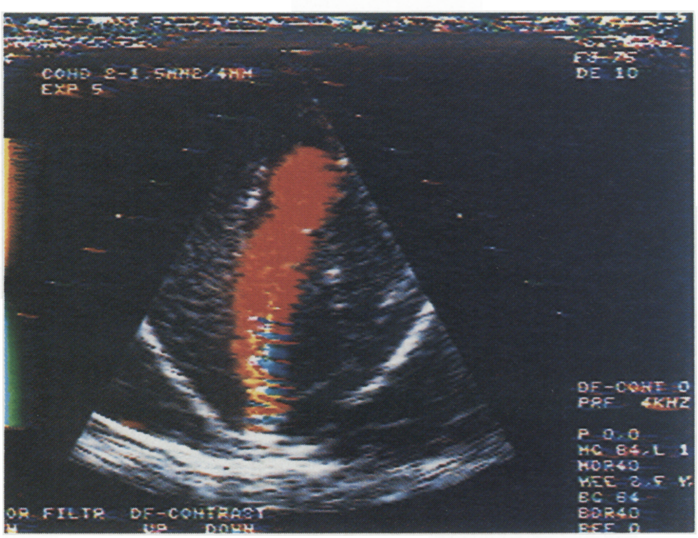

FIGURE 5. *Color Doppler image showing more velocity variance (turquoise, orange, and white) and reverse (blue) velocity encoded pixels on the surface side of the jets, where a curved surface, at the right of the jet, was placed 4 mm away from the jet origin. The color disturbances are in accordance with the greater flow disturbances in the shear layer between the surface and the jet.*

whole had more evidence of velocity variation and variance encoding.

Intraobserver and Interobserver Variability

Intraobserver variability for jet area measurements was within 5%, while the interobserver variability was less than 8%.

Discussion

Jets have been studied extensively in engineering, primarily as free turbulent shear flows.[19–31] Although it has been known for decades that jets occur in the heart during abnormal conditions, only recently has there been a concerted approach toward studying the relations between the fundamental nature of such flows and the corresponding cardiac pathologies.[32–35] Many of these in vitro studies were designed to evaluate the use of color Doppler flow mapping to image flows modeled after those occurring in valvular diseases.[36–38] Very few experiments, however, dealt with the more realistic situation of jets flowing and interacting within the confines of a receiving chamber.[39] In this experiment we used color Doppler flow mapping to study one such specific case: a jet interacting with an adjacent solid surface inside the receiving chamber.

This phenomenon of jet flow being attracted to an adjacent surface was first described in the engineering literature by Henri Coanda in 1910.[14,40] Five decades later, the Coanda effect was offered as an explanation for unequal systolic blood pressure in the upper extremities for cases of supravalvular aortic stenosis.[15] In this study, French and Guntheroth proposed that aortic narrowing at the location of the supravalvular stenosis creates a Coanda effect whereby the jet of blood adheres to one side of the aortic wall, creating unequal flow distribution and pressures in the brachial and carotid arteries.[15]

In our experiment, we focused on the differences in color Doppler imaging of free and surface-adherent jets. From engineering studies, we know that as a free jet leaves a nozzle into a receiving chamber, a turbulent shear layer develops between the receiving chamber fluid and the inflow jet stream boundary.[21–28] The shear layer will eventually consume the core of the jet, from which point the jet becomes fully developed or freely turbulent.[19,22,29–31] All sides of the jet are equally affected, and although the width of the jet experiences instantaneous changes, the jet expands symmetrically and mean jet width will also grow over time in a balanced fashion, resulting in a symmetrical jet flow.[19,21] It is also known that as the jet intrudes into the receiving chamber, vortex motion entrains surrounding fluid.[30,31] These vortices envelop and drag in pockets of stagnant fluid, increasing jet mass and decreasing flow velocity, and jet kinetic energy transforms into jet stream expansion.[11,17,21–28]

When a surface is placed beside the nozzle, stagnant flow entrainment through the jet's large-scale vortex structures is inhibited on the surface side of the jet, creating an asymmetric shear layer between the jet stream and the surface.[41–43] Viscous (drag) forces acting from the surface in the direction opposite to the jet flow retard the flow adjacent to the surface.[44,45] Because mass entrainment is retarded on the surface side and because flow momentum must be conserved throughout the jet, flow velocities on the surface side of the jet will be higher than the velocities on the free side.[46] However, since flow velocity at the surface must be zero because of viscosity and the no-slip condition, spatial transverse velocity gradients will be significant, leading to high shearing forces and increased viscous effects that "pull" the jet flow toward the surface.[47,48]

Although it is well understood that jet area measurement is not a good quantitative indicator of flow volume and valvular disease severity, it is still widely used as an immediate qualitative index for evaluating valvular disease.[49–51] Furthermore, the advent of sophisticated computer image processing systems has made it possible for investigators to extract parameters such as momentum, spatial acceleration, variance intensity, and kinetic energy from the color Doppler images, and these have been correlated with greater success to flow hydrodynamics.[18,33,52] For these reasons, we decided to perform this in vitro study to observe how fundamental changes in jet flow dynamics caused by the proximity of an adjacent surface could influence color Doppler imaging of such flows and thereby affect currently used procedures for evaluation of color Doppler images.

We have demonstrated that the Coanda effect may influence jet size and color encoding in color Doppler imaging. All the jet flows with an adjacent surface present had smaller jet areas and more variance and reverse flow pixels than the free jets, especially on the surface side. The distance between the surface and the inflow orifice was also a major determinant of the jet size. We chose 4 mm as an appropriate surface-to-orifice distance from observations in previous studies involving parallel dual jet flow, which is hydrodynamically similar to surface jet flow.[53] In these studies we observed the strongest jet deviation when the dual jets were between 0 and 4 mm.[53] Because we have also observed that a solid surface affects jet interaction more strongly than an adjacent jet flow, we decided to place the surface at a distance that could still be resolved on the ultrasound scanner and that would provide strong viscous interaction.[54] For this present study, we again observed that if the surface was moved farther than 4 mm away from the inflow orifice, very little jet deviation occurred. As has previously been observed, the shearing force of the jet stream against the surface is greater when the surface comes closer to the orifice of the inflow jet, causing stronger attraction of the flow by the surface.[41]

The proximity of the surface also seems to be more important than the surface shape (convex or straight). We observed larger areas for jets with surfaces 4 mm away from the orifice than for jets with surfaces adjacent to it but did not see any differences in jet areas caused purely by surface shape. This could be explained by the fact that even the curved

surface is, in effect, still relatively straight in the vicinity of the proximal or core portion of the jet, which contains high-velocity forward flow components and less shear stress at the boundary. By the time the surface curves away from the jet, velocity has fallen, the jet is adherent, and the outer jet velocities eventually have decayed below the color Doppler threshold and so will not be displayed. This lack of difference in jet area for surfaces with different shapes cannot be generalized for surfaces concave to the flow because of the fundamental differences between the two situations. For our studies with straight and convex surfaces, flow adherence is purely a result of surface attraction, where the vicinity of a surface creates a change in the nature of the flow, which in turn affects flow behavior in the form of jet stream diversion onto the surface.[41–46] For jet flow encountering a concave surface, the jet is cradled by the surface, and flow changes caused entirely by surface adherence become secondary to the impingement-type effect of the concave surface.

In addition to changes in jet flow area, we also observed marked differences in how the color Doppler scanner displayed the jet. The pixels within the jets along the surface showed greater numbers of green (variance) and blue (reverse velocity) pixels encoded along the surface side than on the free side of jet, indicating reverse flow and greater disorganization of flow velocities along the surface side. The larger amount of green on the surface side is consistent with the fact that the surface side of the jet, the shear layer, contains high spatial velocity gradients as a result of the greater shear stresses at this boundary creating large and varying frequency shifts in the returned Doppler frequencies. Although there were significantly higher numbers of green pixels on the surface side of the surface jets than the surface side for free jets, the numbers of green pixels on the surface side of the surface jets were different from those on the free side of the surface jets, but not significantly so. We believe that this is because of the relatively small size of these jets and because the complex hydrodynamics associated with the entrainment zone may cause the ultrasound scanner to encode green even on the nonsurface side of the jet. The further degradation of the images caused by limited bandwidth of the composite video format in which the images were recorded may cause further diffusion of green color throughout the relatively small area that represents the color Doppler jet. The increased blue on the surface side also agrees with engineering observations of flows along a surface curving away from the flow. An adverse (negative) pressure gradient similar to that at the origin of a wake exists at the location where the surface curves away from the jet, creating opposing forces that generate secondary flow and vortex motion.[55] Secondary flow caused by adverse pressure gradients has also been shown to exist along straight surfaces, although to a lesser extent than with curved surfaces.[39] Since secondary flow contains reverse velocities, it is no surprise that the color Doppler flow maps show blue along the surface side of the jet images.

There are several important limitations to our study. We did not study high flow rates, because jet size, increasing with flow rate, showed color spreading beyond the image sector for high flow rates and could not be measured. For higher flow rates and velocities, the shape of the surface and especially the position and angle of a curved surface may play important roles in affecting color Doppler imaging of surface-adherent jets. In addition, the jet stream is spatially three dimensional, and we measured only one plane and so could not see changes of the jet width in the plane at right angles to the one we used along the surface. The orthogonal plane showing the jet "on" the surface,[56] however, would be an unusual view on an echo exam. Most planes used in clinical echocardiography are not angled onto the surfaces but rather are perpendicular to them. Furthermore, we did not use concave surfaces to compare differences among jet area measurements using convex, straight, and concave surfaces. In fact, the initial adherence of the jet coming through the mitral commissures in mitral regurgitation and especially in mitral prolapse is to the back of the mitral leaflets, and hence, the jet is directed to the atrial wall. The initial adherence and energy loss are therefore occurring on the convex surface of the back side of the mitral valve (Figure 1B). The same convex surface adherence occurs on the septal surface relevant to adherent aortic regurgitation jets. The events of viscous energy loss and surface adherence that occur on convex surfaces are more commonly observed in clinical imaging and may be more fundamentally interesting than the impingement and confining of jets on concave surfaces, which limits jet spread by constraint and a ricochet of secondary flow velocities back toward the direction of their origin.

When color Doppler flow mapping was first clinically applied, measurement of abnormal flow jet areas, such as regurgitant flow jets, was widely used as a basis for grading the severity of valvular regurgitation, because the assumption that a larger regurgitant jet area indicates a larger regurgitant volume appeared to be supported by several in vivo studies using angiographic grading of the severity of aortic and mitral regurgitation.[36–38] Subsequent studies failed to validate these results, however, and flow jet area is now no longer considered to be a reliable indicator of flow volume.[57,58] Other investigators have demonstrated that flow jet area is dependent on flow velocity and kinetic energy,[11,17] and we now understand that the jet area mapped with color flow mapping reflects not only the velocity and mass of the original flow jet itself but also the entrained and displaced parajet fluid flow. For an eccentric regurgitant jet close to the left atrial wall or the ventricular septum, the regurgitant jet will almost always adhere to the wall or septum, which may cause jet stream flattening, making the jet appear smaller, with consequent underestimation of the measured severity of valvular regurgitation in color flow mapping.

In addition to surface interactions, other receiving chamber factors such as compliance and ambient pressure may also change jet area (color encoded jets appear smaller in a high-pressure, low-compliance receiving chamber).[39] For this reason as well as others, we believe that an approach to transvalvular regurgitant flow quantitation based on a study of a more organized and laminar zone, such as the proximal flow convergence within the source chamber of a jet, for instance, the left ventricle in mitral insufficiency,[35] may be a more fruitful and rational approach to quantitation of color flow Doppler than attempting to quantitate the disorganized flow areas within the receiving chamber.

References

1. Perry GJ, Helmcke F, Nanda NC, Byard C, Soto B: Evaluation of aortic insufficiency by Doppler color flow mapping. *J Am Coll Cardiol* 1987;9:952–959
2. Helmcke F, Nanda NC, Hsiung MC, Soto B, Adey CK, Goyal RG, Gatewood RP: Color Doppler assessment of mitral regurgitation with orthogonal planes. *Circulation* 1987;75: 175–183
3. DeMaria AN, Spain MG, Garrahy P, Grayburn PA, Kwan OL, Smith MD: Considerations in the quantitation of color Doppler flow imaging. *Echocardiography* 1987;4:495–499
4. Jones M, Hoit B, Eidbo E, Meyer T, Sahn DJ, Elias B: Variability of Doppler color flow mapping imaging of regurgitant jets in an animal model of mitral insufficiency (abstract). *J Am Coll Cardiol* 1987;9:64A
5. Lobodzinski SM, Nanda NC: Computer quantification of Doppler color flow images with clinical applications. *Echocardiography* 1988;5:427–437
6. Bolger AF, Eigler NL, Pfaff MJ, Maurer F, Resser KJ, Maurer G: Computer analysis of Doppler color flow mapping images for quantitative assessment of in vitro fluid jets. *J Am Coll Cardiol* 1988;12:450–457
7. Aggarwal KK, Philpot EF, Moos S, Yoganathan AP, Nanda NC: Color Doppler flow mapping: Intra and inter-machine variability for low flow velocities in an in vitro model (abstract). *J Am Coll Cardiol* 1988;11(suppl A):98A
8. Grayburn PA, Pryor SL, Levine BD, Klein BD, Taylor AL: Day to day variability of Doppler color flow jets in mitral regurgitation. *J Am Coll Cardiol* 1989;14:936–940
9. Bolger AF, Eigler NL, Maurer G: Quantifying valvular regurgitation limitations and inherent assumptions of Doppler techniques. *Circulation* 1988;78:1316–1318
10. Tamura T, Elias W, Gunday E, McMillan S, Jimoh A, Yoganathan A, Chung K: In vitro studies of variance (turbulence) indicators in Doppler color flow mapping systems: Quantitative computer analysis of RGB digitized flow map images (abstract). *Circulation* 1987;76(suppl IV):IV-141
11. Sahn DJ: Instrumentation and physical factor related to visualization of stenotic and regurgitant jets by Doppler color flow mapping. *J Am Coll Cardiol* 1988;12:1354–1368
12. Smith MD, Grayburn PA, Spain MG, DeMaria AN: Observer variability in the quantitation of Doppler color jet areas for mitral and aortic regurgitation. *J Am Coll Cardiol* 1988;11: 578–584
13. Chen C, Thomas JD, Anconina J, Harrigan P, Levine RA, Weyman AE: Impact of eccentrically directed impinging wall jets on quantitation of mitral regurgitation of color Doppler flow mapping (abstract). *Circulation* 1989;80(suppl II):II-578
14. Reba I: Applications of the Coanda effect. *Sci Am* 1966;214: 84–92
15. French JW, Guntheroth WG: An explanation of asymmetric upper extremity blood pressure in supravalvular AS: The Coanda effect. *Circulation* 1970;42:31–36
16. Goldstein RE, Epstein SE: Mechanism of elevated innominate artery pressures in supravalvular aortic stenosis. *Circulation* 1970;42:23–29
17. Simpson IA, Valdes-Cruz LM, Yoganathan AP, Sung HW, Jimoh A, Sahn DJ: Spatial velocity distribution and acceleration in serial subvalve tunnel and valvular obstruction: An in vitro study using Doppler color flow mapping. *J Am Coll Cardiol* 1989;13:241–248
18. Shandas R, Belot JP, Cali G, Moises VA, Sahn DJ: Comparison of analog and digital methods of transferring color Doppler image data for off-line analysis (abstract). *J Am Coll Cardiol* 1990;15:89-A
19. Rajaratnam N: *Developments in Water Science: Turbulent Jets.* New York, Elsevier Science Publishing Co, Inc, 1976, pp 211–215
20. Yoganathan AP, Cape EG, Sung HW, Williams FP, Jimoh A: Review of hydrodynamic principles for the cardiologist: Applications to the study of blood flow and jets by imaging techniques. *J Am Coll Cardiol* 1988;12:1344–1353
21. Abramovich GN; Scripta Technia, trans: *The Theory of Turbulent Jets.* Cambridge, Mass, MIT Press, 1963, pp 173–234
22. Roshko A: Structure of turbulent shear flows: A new look. *Am Inst Aeronautics & Astronautics J* 1976;14:1349–1357
23. Brown GL, Roshko A: On density effects and large structure in turbulent mixing layers. *J Fluid Mech* 1974;64:775–816
24. Stewart RW: Turbulence, in *Illustrated Experiments in Fluid Mechanics* [16 mm sound film and accompanying text]. Cambridge, Mass, MIT Press, 1972, pp 82–88
25. Liepmann HW, Laufer J: Investigations of free turbulent mixing. National Advisory Committee for Aeronautics, technical note No. 1257, August 1947, pp 1–30
26. Rodi W (ed): *Turbulent Buoyant Jets and Plumes.* Oxford, Pergamon Press, Inc, 1982, pp 1–62
27. Andrade EN, Tsien LC: The velocity distribution in a liquid-into-liquid jet. *Proc Phys Soc London* 1937;49:381–390
28. Wyganski I, Fiedler H: Some measurements in the self-preserving jet. *J Fluid Mech* 1969;41:327–361
29. Blevins RD: *Applied Fluid Dynamics Handbook.* New York, Van Nostrand Reinhold Co, Inc 1984, pp 1–21
30. Becker HA, Massaro TA: Vortex evolution in a round jet. *J Fluid Mech* 1968;31:435–448
31. Cohen J, Wyganski I: The evolution of instabilities in the axisymmetric jet. Part 1: The linear growth of disturbances near the nozzle. *J Fluid Mech* 1987;176:191–219
32. Wranne B, Ask P, Loyd D: Quantification of heart valve regurgitation: A critical analysis from a theoretical and experimental point of view. *Clin Phys* 1985;5:81–88
33. Thomas JD, Liu CM, Flachskampf FA, O'Shea JP, Davidoff R, Weyman AE: Quantification of jet flow by momentum analysis: An in vitro color Doppler flow study. *Circulation* 1990;81:247–259
34. Krabill KA, Sung HW, Tamura T, Chung KH, Yoganathan AP, Sahn DJ: Factors influencing the structure and shape of stenotic and regurgitant jets: An in vitro investigation using Doppler color flow mapping and optical flow visualization. *J Am Coll Cardiol* 1989;13:1672–1681
35. Recusani F, Bargiggia GS, Yoganathan AP, Raisaro A, Valdes-Cruz LM, Sung H-W, Bertucci C, Gallati M, Moises VA, Simpson IA, Tronconi L, Sahn DJ: A new method for quantification of regurgitant flow rate using color Doppler flow imaging of the flow convergence region proximal to a discrete orifice: An in vitro study. *Circulation* 1991;83:594–604
36. Perry GJ, Helmcke F, Nanda NC, Byard C, Soto B: Evaluation of aortic insufficiency by Doppler color flow mapping. *J Am Coll Cardiol* 1984;9:952–959
37. Spain MG, Smith MD, Grayburn P, Harlamert EA, DeMaria AN: Quantitative assessment of mitral regurgitation by Doppler color flow imaging: Angiographic and hemodynamic correlations. *J Am Coll Cardiol* 1989;13:585–590
38. Pearlman AS, Otto CM: Quantification of valvular regurgitation. *Echocardiography* 1987;4:271–287
39. Maciel BC, Moises VA, Shandas R, Simpson IA, Beltran M, Valdes-Cruz LM, Sahn DJ: Effects of pressure and volume of the receiving chamber on the spatial distribution of regur-

gitant jets as imaged by color Doppler flow mapping: An in vitro study. *Circulation* 1991;83:605–613
40. Willie R, Fernholz H: Report of the first European mechanics colloquium on the Coanda effect. *J Fluid Mech* 1965;23: 801–810
41. Liepmann D: The near-field dynamics and entrainment field of submerged and near-surface jets (dissertation). San Diego, Calif, University of California San Diego, 1990
42. Newman BG, Patel RP, Savage SB, Tjia HK: Three-dimensional wall jet originating from a circular orifice. *Aerodynamics Quarterly* 1972;23:188–200
43. Ramaprian BR: Turbulence measurements in an 'equilibrium' axisymmetric wall jet. *J Fluid Mech* 1975;71:317–338
44. Chandrasekhara Swamy NV, Bandopadhay P: Mean and turbulence characteristics of three-dimensional wall jets. *J Fluid Mech* 1975;71:541–562
45. Sforza P, Herbst G: A study of three-dimensional incompressible turbulent wall jets. *AIAA J* 1969;8:276–283
46. Curtis ES, Pai SI, Weske JR: Some experimental studies on wall jets. *Proceedings of the Fifth US Congress of Applied Mechanics.* New York, American Institute of Aeronautics and Astronautics, pp 749–751
47. Rajaratnam N, Humphries JA: Turbulent non-buoyant surface jets. *Can J Hydraulics Res* 1984;22:103–114
48. Freymuth P: On transition in a separated boundary layer. *J Fluid Mech* 1966;25:683–704
49. Miyatake K, Isumi S, Okamoto M, Kinoshita N, Asonuma H, Nakagawa H, Yamamoto K, Takamiya M, Sakakibara H, Nimura Y: Semiquantitative grading of severity of mitral regurgitation by real-time two dimensional Doppler flow imaging technique. *J Am Coll Cardiol* 1986;7:82–88
50. Sahn DJ: Real-time two dimensional echocardiographic flow mapping. *Circulation* 1985;71:849–853
51. Switzer DF, Yoganathan AP, Nanda NC, Woo Y, Ridgway AJ: Calibration of Doppler color flow mapping during extreme hemodynamic conditions in vitro: A foundation for a reliable quantitative grading system for aortic incompetence. *Circulation* 1987;75:837–846
52. Shandas R, Golebiovski P, Valdes-Cruz LM, Jones M, Murillo A, Yamada I, Sahn DJ: A new automatic computer method for measuring mean flow convergence radius from color MQ modes provides more accurate flow rate estimates: In vitro and animal studies of mitral regurgitation (abstract). *J Am Coll Cardiol* 1991;17:148A
53. Shandas R, Moises V, Maciel B, Liepmann D, Sahn DJ: Demonstration of jet entrainment—An interaction that causes parallel jets to merge and cross: In-vitro experiments using color Doppler flow mapping and optical visualization (abstract). *J Am Coll Cardiol* 1989;13:25A
54. Shandas R, Moises V, Maciel B, Liepmann D, Sahn DJ: Quantitative factors affecting parallel jet and jet surface interactions: An in-vitro study by color Doppler and optical visualization (abstract). *J Am Coll Cardiol* 1990;15:121A
55. Meiburg E, Lasheras JC, Ashurst WT: Topology of the vorticity field in three-dimensional shear layers and wakes. *Fluid Dyn Res* 1988;3:140–148
56. Cape EG, Yoganathan AP, Weyman AE, Levine RA: Adjacent solid boundaries alter the size of regurgitant jets on Doppler color flow maps. *J Am Coll Cardiol* 1991;17: 1094–1102
57. Davidoff R, Wilkins GT, Thomas JD, Achorn DM, Weyman AE: Regurgitant volumes by color flow overestimate injected volumes in an in-vitro model (abstract). *J Am Coll Cardiol* 1987;9:110A
58. Harlamert EA, Smith MD, Spain MG, Gash DL, Berk MR, DeMaria AN: Color Doppler flow imaging underestimates the severity of acute mitral regurgitation (abstract). *Circulation* 1988;78(suppl II):II-434

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