Intramachine and Intermachine Variability in Transesophageal Color Doppler Images of Pulsatile Jets

In Vitro Studies

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Background Color Doppler flow mapping is widely used as a marker of severity of valvular regurgitation, and the transesophageal approach has provided high-quality images in patients with poor acoustic windows. However, different instruments produce significantly variable images. Techniques that use jet spatial information to determine the severity of the lesion may need to be derived specifically for the instrument used. Given a lack of standardization of the many commonly used instruments, the goal of this study was to quantify variability between instruments by imaging well-defined jet flow fields created in vitro.

Methods and Results Pulsatile jets were created in vitro using a blood analogue fluid through physiological orifice diameters and imaged from a distal window using six commonly used color Doppler instruments. Transesophageal transducers (5.0 MHz) were used with all instruments studied. Peak jet areas were planimetered and averaged with systematic variations in Nyquist limit, color filter, and sector angle (which produced variations in frame rate). Changes in instrument settings produced significant variation in jet size for all instruments studied. Comparisons within instruments and among instruments were difficult because of preset and ambiguous setting levels. When comparisons were possible between similar settings, variability was dramatic (eg, 57% variability between instruments with very similar Nyquist limits).

Conclusions A lack of standardized color Doppler instrument settings prohibits translation of jet area techniques from one instrument to another. This should be taken into consideration when using different machines for clinical study. **(*Circulation*. 1994;89:2141-2149.)**

Key Word • echocardiography

Doppler color flow mapping is a modality frequently used in clinical cardiology to visualize the position, direction, and extent of jets and accelerating flows through regurgitant valves. Although color Doppler allows "real-time" visualization of these jets, it provides only a mean value of the Doppler velocity, unlike pulsed and continuous wave modalities, which produce a spectral distribution of velocities. Although not as accurate as the flow information from continuous or pulsed Doppler techniques, these images are a vital supplement in analyzing and comparing information from complicated flow fields such as that in valvular regurgitation.

As discussed in detail previously,[1-3] color Doppler provides flow information from multiple sample volumes along a scan line through the use of autocorrelation methods to analyze the differences between the transmitted and received sound waves, thus providing information about velocity direction and magnitude. As noted above, however, use of the autocorrelation technique provides only mean velocity information. The color information that is finally displayed on the color flow monitor is the outcome of processed signal information by the color flow map algorithms and the interaction of various instrument settings.[4-9] Because of the numerous color Doppler manufacturers, varying algorithms and instrument settings produce different images for the same flow depending on the chosen instrument. This presents a fundamental problem when image size (eg, regurgitant jet area) is used to assess the lesion. Although the effect of instrument settings within a given machine has been assessed by various investigators,[4-9] no comprehensive study has been performed to investigate the influence of various instrument settings on the presentation of flow information by different machines.

The purpose of the present study was therefore to investigate this variability. We addressed the question of whether color Doppler flow area measured by one color Doppler system can be reproduced on other commercially available systems and how different machine factors such as Nyquist limit, color sector angle, frame rate, and color filter would influence the size of the color Doppler flow area in each case. This study should have immediate clinical relevance because regurgitant jet areas imaged by color Doppler are com-

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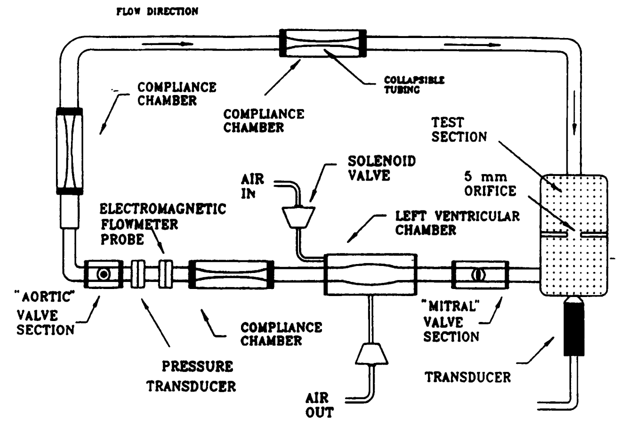

FIG 1. Schematic of pulsatile flow device.

monly used as a marker of severity of valvular regurgitation.

Methods

Six different color Doppler machines were used for this study—the Vingmed 750, the Aloka 870, the Acuson 128, the Hewlett Packard 1000, the Advanced Technology Laboratories Ultramark 9, and the Toshiba 160A. Each machine was used to image pulsatile flow jets of a water/glycerine solution through a 5-mm circular orifice. The solution was 40% glycerine by weight. Sand particles (2 to 3 μm mean diameter; 2% by weight) were used as acoustic scatterers, and ultrasound coupling gel was used for improved acoustic coupling.

The pulsatile flow system is shown in Fig 1. It is an air-regulated system that includes a valve section, a left ventricular bulb, and various compliance chambers to provide physiological flow and pressure waveforms. The flow is pushed forward to the Plexiglas tank and through the orifice when the left ventricular bulb is compressed. In the diastolic part of the cycle, the bulb is filled with liquid from proximal portions of the system, although the liquid is prevented from being drawn from distal regions by an "aortic" valve. Flow is prevented from moving in reverse during systole by a "mitral" valve proximal to the flow. Volumetric flow and pressure were monitored by a Validyne pressure transducer and a Nihon Kohden electromagnetic flowmeter, respectively. A more detailed description of the flow system has been described previously.[10]

A 5.0-MHz transesophageal transducer was interfaced to the Plexiglas chamber, as shown in Fig 1, in such a way that the ultrasound beam would be parallel to the direction of the flow

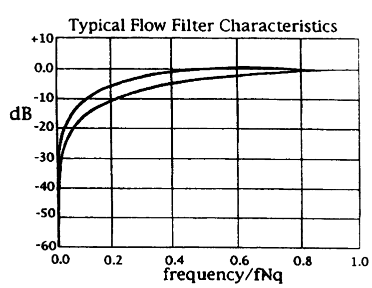

FIG 2. Typical flow filter characteristics. Schematic shows two flow filter profiles with cutoff frequency expressed as a function (f) of Nyquist limit (Nq) and displayed on horizontal axis. Vertical axis allows determination of cutoff frequency for different levels of gain shown in decibels (dB). Of note is the fact that the relation between frequency and gain is not constant. Also, slopes of filters become steeper at lower Doppler frequencies.

in the chamber. The transducer was held in place by a clamp and labstand device, and coupling gel was used between the transducer and Plexiglas surface. A peak velocity of 0.8 m/s was used throughout the experiment and was checked in each phase of the experiment by continuous wave Doppler. This flow velocity allowed the baseline color flow images to be optimally visualized and measured, and the low value was specifically chosen to minimize aliasing. The corresponding peak volume flow rate of 0.94 L/min was also monitored by the electromagnetic flowmeter probe as a double check.

On optimizing the color Doppler gain in a standard manner,[11,12] the maximal baseline color Doppler flow area was planimetered and measured using prestored cine-loop frames. The instrument settings listed above were then varied, and the color Doppler flow area measurements were repeated and compared with baseline. The maximal color Doppler flow areas were measured using three different imaging frames, and the average was taken for analysis. The same process was repeated on a different day to ensure reproducibility of the results. All measurements were performed by two independent observers. Twenty-one randomly selected color flow area measurements were analyzed for interobserver variability. Synchronizing the pump with the scan raster to ensure that maximal jet image is obtained would have made the frame rate underestimations less severe. This, however, is not practiced clinically. It was our goal to determine the change in jet size with frame rate using typical clinical instruments and settings. In the clinical setting, frame rate and heart rate are not synchronized and thus interact from a random starting point, as used in this study.

The maximal changes of color Doppler flow areas (compared with baseline) resulting from each alteration of the instrument setting from the same and different machines were compared using one-way ANOVA and Student's t test to test statistical significance. Interobserver variability in the measurement of the maximal color flow area was tested using linear regression analysis, which yields a correlation coefficient and SEE.

Results

The general trend was that the reduction of Nyquist limit resulted in an increase in color Doppler flow area (Table 1 and Fig 3). However, for almost identical values of Nyquist limit, different machines showed a great variation (as much as 57%) in color Doppler flow area. Some machines consistently showed a smaller color Doppler flow area value for the same Nyquist limit; however, it was not possible to obtain a statistically consistent relation between color Doppler flow areas from different machines. There was no significant difference in the measurement of color Doppler flow areas between the two independent observers. The correlation coefficient was excellent (r=.93).

A study between low and high color filter settings could be compatible only between the Toshiba 160A and the Aloka 870. For identical values of Nyquist limit of 0.32 m/s, frame rate of 7 Hz, and sector angle of 80° as shown in Table 2, a change from high filter to low filter showed a significant increase in color flow area (Fig 4).

The results for each individual machine are summarized below followed by a detailed discussion of intramachine and intermachine variability.

Individual Instrument Study

For the Vingmed 750 instrument, different values of the Nyquist limit were chosen for the peak velocity of

Table 1. Effect of Changes in Nyquist Limit on Color Doppler Flow Areas for Different Color Doppler Instruments

	Hewlett Packard 1000	Aloka 870	Acuson 128	Toshiba 160A	Vingmed 750	Advanced Technology Laboratories Ultramark 9
NYL, m/s	0.47	0.46	0.38	0.4	0.42	0.39
	(FR=14 Hz, D=10 cm)	(FR=15 Hz, D=12 cm)	(FR=20 Hz, D=12 cm)	(FR=14 Hz, D=12 cm, CF=360 Hz)	(FR=25 Hz, D=12 cm)	(FR=8 Hz, D=13 cm, CF=400 Hz)
CDA, cm²*	11.2	19.5	12.8	12.8	9.0	14.1
NYL, m/s	0.26	0.32	0.27	0.2	0.23	0.27
	(FR=10 Hz, D=20 cm)	(FR=10 Hz, D=15 cm)	(FR=16 Hz, D=20 cm)	(FR=10 Hz, D=20 cm, CF=360 Hz)	(FR=14 Hz, D=12 cm)	(FR=6 Hz, D=13 cm, CF=400 Hz)
CDA, cm²*	13.6	21.0	13.83	14.9	13.7	18.4
CDA, % increase	21.4	7.7	8.0	16.41	52.2	30.5

NYL indicates Nyquist limit; CDA, color Doppler flow area; FR, frame rate; D, depth; and CF, color filters.
Flow velocity was 0.8 m/s, and sector angle was 45°.
*$P<.001$ for all values.

0.8 m/s at the orifice, and the corresponding values of color Doppler flow area in squared centimeters were recorded. The results shown in Table 3 indicate that reduction in Nyquist limit produces an increase in color Doppler flow area for both narrow (45°) and wide (70°) sector angles.

Similarly, for the Aloka 870 instrument, two different values of the Nyquist limit were recorded for the low-filter setting and the high-filter setting of the machine. These measurements were recorded for a 45° and an 80° image sector angle, whereas the scan depth remained constant at 12 cm. Reduction of color Doppler flow area with increased Nyquist limit was observed again, as shown in Table 4. The color Doppler area in the high-filter mode was lower as expected. The values of color Doppler areas were higher compared with the Vingmed 750 results, whereas the values of the Nyquist limit for the two machines were comparatively similar.

The Acuson 128 instrument was examined next. For two different image sector angles, different Nyquist limits were imposed, and the corresponding color Doppler areas were recorded; the results are shown in Table 5. Under these conditions, the scan depth remained constant at 10 cm, but the frame rate changed, as shown in the table. In general, the same trends as described above were observed.

For the Hewlett Packard 1000 machine, changes in the Nyquist limit resulted in simultaneous changes in the scan depth (Fig 5) and frame rate. Two image sector angles of 45° and 90° were used, and the color Doppler flow area values recorded are shown in Table 6. In agreement with our previous results, increasing the Nyquist limit resulted in a decrease in the color Doppler area for both sector angles.

A similar procedure was followed for the Advanced Technology Laboratories Ultramark 9 instrument. The Nyquist limit was varied with simultaneous changes in the frame rate. The corresponding changes in color Doppler area obtained are shown in Table 7. The color filter settings of the machine were also altered, and the respective recorded color Doppler areas are shown in Table 8.

Again, as seen before, the Toshiba 160A instrument showed that changes in the Nyquist limit resulted in simultaneous changes in the scan depth and frame rate. Two image sector angles of 45° and 90° were used, and the recorded color Doppler flow area values are shown in Table 9. In accordance with our previous results,

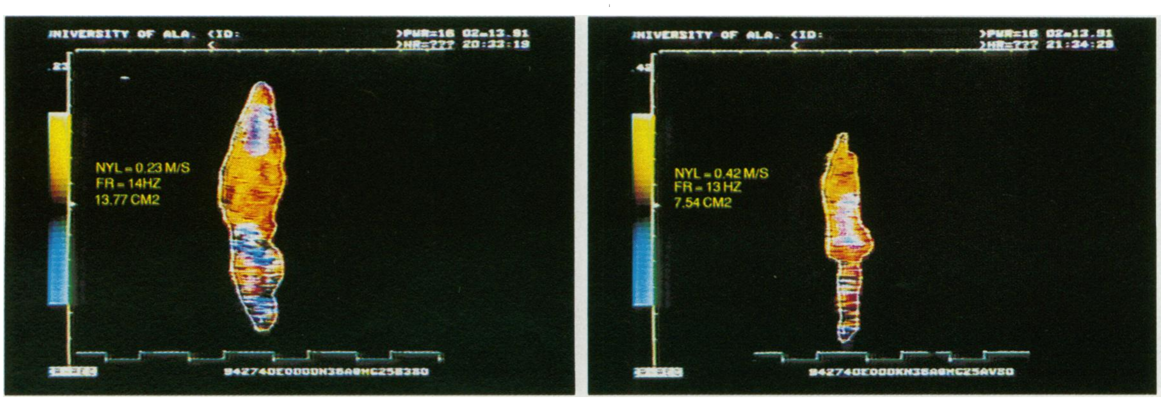

Fig 3. Effect of Nyquist limit (NYL) on color Doppler area (CDA) (Toshiba 160A). A change in NYL from 0.23 m/s (A) to 0.42 m/s (B) results in a decrease in CDA from 13.77 cm² to 7.54 cm². Other parameters, such as peak flow velocity, image depth, and color filter, were kept constant.

Table 2. Effect of Changes in Color Filter on Color Doppler Flow Areas (Toshiba 160A and Aloka 870)

	High Color Filter	Low Color Filter	CDA, % change
Toshiba 160A, CDA, cm^2*	11.15 (CF=360 Hz)	19.8 (CF=60 Hz)	78
Aloka 870, CDA, cm^2*	11.8 (CF=400 Hz)	19.6 (CF=80 Hz)	66
CDA, % change	+5.8	−1.0	...

CDA indicates color Doppler flow area.

Flow velocity was 0.8 m/s, Nyquist limit was 0.32 m/s, frame rate was 7 Hz, and sector angle was 80°.

**$P<.001$ for all values.*

increasing the Nyquist limit resulted in decrease of the color Doppler flow area for both sector angles. This machine, however, allowed individual variation of the frame rate at a constant Nyquist limit. The corresponding variation of the color Doppler flow area is shown in Table 10.

Discussion

Color Doppler flow mapping has become a widely used tool in the clinical assessment of valvular lesions.[13,14] With the ability to visualize regurgitant jets, the possibility of noninvasive assessment of valvular insufficiency seemed imminent when color Doppler was introduced in the early 1980s. Measurements of jet spatial extent (eg, ratio of jet area to left atrial area or jet area only in mitral regurgitation) were shown to correlate well with angiography.[11,15] These measurements are widely used today, at least as a marker of the severity of regurgitation, taking advantage of the ability to perform serial studies, which are not practical with cardiac catheterization.

Although the basic concept of jet size correlation with regurgitant flow is sound, factors independent of regurgitation related to instrumentation and physical effects have recently been demonstrated as important.[4-9] It is, therefore, important to account for and understand these factors so that color jet areas can be analyzed judiciously. Variations in jet size for constant degrees of flow have been shown to be significant as a function of instrument settings within a given machine. Because different manufacturers use different data processing and display algorithms, further variability is expected from instrument to instrument. In the same sense as above, then, these variations must be investigated so that the reported results for one instrument can be used cautiously by users of another instrument.

Intramachine Variability

The present comprehensive study of six color Doppler instruments revealed significant intramachine variability. Most disturbing was the fact that Nyquist limit significantly affected jet size. Within the chosen limits, color jet area changed by as little as 7.7% (Aloka) and as much as 52.2% (Vingmed) (Table 1). In principle, Nyquist limit should not affect jet size. It represents the velocity at which flow aliases and is responsible for the mosaic pattern observed in many turbulent jets, but it should not affect the "size" of a jet, which is determined essentially by the level of the high-pass filter, which determines color appearance and disappearance on the flow map. It seems that changes in Nyquist limit are accompanied by redefinition of the wall filter or at least by an automatic alteration in the magnitude of the gain setting.

Some machines allow separate manipulation of the wall filter setting, an increase that should produce a smaller jet. This was found to be the case, for example, for the Toshiba and Aloka instruments (Table 2), where simple changes in wall filter from high to low produced changes of 78% and 66% in jet area, respectively.

Variations in sector angle produce changes in frame rate as well as line density. With all other instrument settings kept constant, changes in jet area were observed with sector size for all instruments studied. These changes, however, were not consistent. With increasing sector angle, both increases and decreases in color jet area were observed, sometimes within a given instrument, depending on the other settings (see Tables 3 through 10).

Increases in frame rate with other settings held constant tended to produced larger images as the probability of sweeping across the pulsatile jet at peak flow was increased (Table 10).

Intermachine Variability

As indicated in Tables 1 through 10, comparisons between color Doppler instruments are virtually impos-

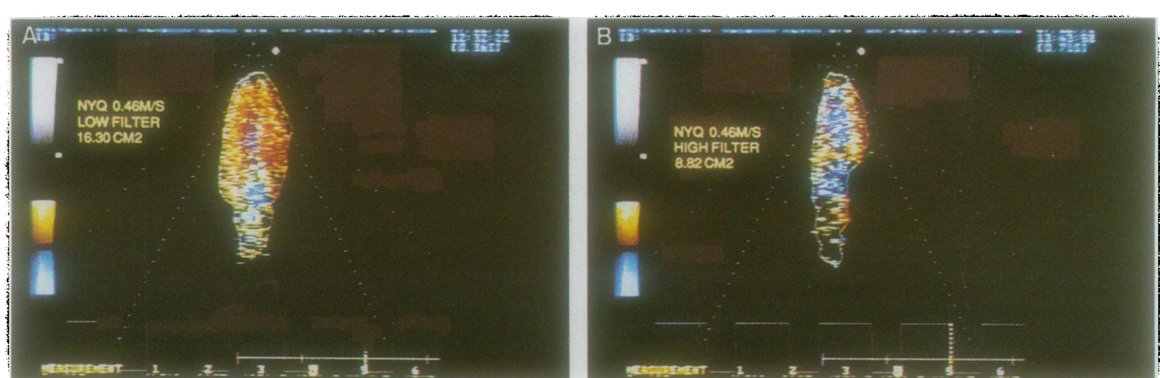

Fig 4. Effect of color filter on CDA (Aloka 870). A change in color filter from low (80 Hz) (A) to high (400 Hz) (B) results in decrease in CDA from 16.30 cm^2 to 8.82 cm^2. Other parameters, such as peak flow velocity, Nyquist limit (NYL), image depth, and frame rate, were kept constant.

Table 3. Effect of Changes in Nyquist Limit on Color Flow Areas for Sector Angles 45° and 70° (Vingmed 750)

	45° Sector Angle			70° Sector Angle		
	0.4 m/s NYL	0.5 m/s NYL	0.6 m/s NYL	0.4 m/s NYL	0.5 m/s NYL	0.6 m/s NYL
Depth, cm	12	14	18	12	14	18
CDA, cm^2	12.99	12.45	11.73	14.67	14.62	12.72
CDA, % change	0	−4.2	−9.7	0	−0.5	−13.3
		P=.001			P=.003	

CDA indicates color Doppler flow area; and NYL, Nyquist limit.
Peak flow velocity was 0.8 m/s, color filter was low, and frame rate was unknown (no indication on this instrument).

sible because of two factors. First, the ability to obtain a consistent group of settings between two instruments, leaving one variable to test, simply is not possible. Second, not only do ambiguous settings such as "low" and "high" preclude comparisons between instruments, but it is questionable whether "low" has a specific meaning instead of varying as other settings are adjusted; for example, it is quite clear from these results that wall filter does not remain constant as the Nyquist limit is varied. Because it is doubtful that the terms "low" and "high" color filter represent the same color cutoff frequencies in different color Doppler machines, this dilemma is symbolic of the difficulty faced when comparing different instruments.

In this study, we found significant variations in jet size with variations in Nyquist limit. As mentioned previously, variations in Nyquist limit should not produce a change in jet size, yet changes in jet size were found for all six instruments we studied. This can be explained as follows: the pulsing frequency of the transducer sets a maximal detectable frequency shift and velocity (Nyquist limit). For a given jet flow, the degree of aliasing within the jet will be affected. There is no reason, however, that jet size (as planimetered along the interface of color appearance and disappearance) should be affected by changes in aliasing patterns within the jet. However, increases in Nyquist limit are most likely accompanied by increases in color filter values. Color filters eliminate low-velocity signals to screen high-amplitude noise returning from cardiac structures. However, increases in color filters also cause a decrease in color jet size by definition as the color/black interface is shifted inward to regions of higher velocity. In this study, increases in Nyquist limit resulted in smaller jets—most likely because of accompanying increases in color filters. However, this information is generally not annotated on the screen, nor is it available within customer operation manuals for most instruments.

Another reason for this discrepancy is the color velocity scale. A change in Nyquist limit is annotated by a change in the color velocity scale. Several nonuniform steps of color intensity variation typically are used to represent the distribution of velocity from maximal negative to maximal positive velocity in such color scales. A specific intensity represents a range of velocities rather than one specific velocity. When the Nyquist limit increases, the color intensity that represented a lower velocity now represents a higher velocity, and this may result in a suppressed color Doppler image.

Many machines impose automatic adjustments in some settings, whereas others are adjusted by the operator. Some of these are necessary; some are not. An example of one that is necessary is a decrease in depth setting with an increase in pulsing frequency. (Although increasing pulsing frequency increases the Nyquist limit, it also introduces the possibility of range ambiguity, which cannot be tolerated in the technique of color flow mapping, where proper spatial location is critical.) At other times, automatic changes are made to produce better pictures or for convenience, but it becomes extremely difficult to interpret results. For example, consider Tables 6 and 7 (Hewlett Packard 1000 and Ultramark 9 results). As the Nyquist limit is increased, color Doppler flow area was found to decrease. Of note, however, is the fact that frame rate also increased automatically. It has been shown that increases in frame rate tend to increase apparent jet size in pulsatile flow due to a higher probability of sweeping across the jet at peak flow.[16] On the other hand, at lower frame rates, the jets may appear to be larger because of degradation of temporal resolution, resulting in superimposition of frames from two adjacent but different times in the

Table 4. Effect of Changes in Color Filters and Nyquist Limit on Color Doppler Flow Areas for Sector Angles 45° and 80° (Aloka 870)

	45° Sector Angle (FR=10 Hz)				80° Sector Angle (FR=7 Hz)			
	0.32 m/s NYL	0.32 m/s NYL	0.46 m/s NYL	0.46 m/s NYL	0.32 m/s NYL	0.32 m/s NYL	0.46 m/s NYL	0.46 m/s NYL
Color filter	Low	High	Low	High	Low	High	Low	High
CDA, cm^2*	18.1	10.77	16.3	8.82	20.0	9.22	16.1	6.92
CDA, % change	...	−40.5	...	−45.9	...	−53.9	...	−57.0

NYL indicates Nyquist limit; CDA, color Doppler flow area; and FR, frame rate.
Peak flow velocity was 0.8 m/s, and depth was 12 cm.
*P<.001 for both sector angles.

Table 5. Effects of Changes in Nyquist Limit on Color Doppler Flow Areas for Sector Angles 45° and 90° (Acuson 128)

	45° Sector Angle			90° Sector Angle		
	0.16 m/s NYL	0.27 m/s NYL	0.38 m/s NYL	0.16 m/s NYL	0.27 m/s NYL	0.38 m/s NYL
FR, Hz	18	16	20	11	10	12
CDA, cm^2	15.22	14.53	13.83	14.57	13.45	11.65
CDA, % change	0	−4.5	−9.1	0	−7.7	−20.0
		P=.001			P=.005	

NYL indicates Nyquist limit; CDA, color Doppler flow area; and FR, frame rate.
Peak flow velocity was 0.8 m/s, depth was 10 cm, and color filters were low.

cardiac cycle.[17] However, the increased Nyquist limit and accompanying color filter effect as discussed above dominate the increased frame rate effect for the two situations studied. Granted, the changes in frame rate were small (6 to 15 Hz for Hewlett Packard 1000 and 3.7 to 8.3 Hz for Ultramark 9), but such changes have been shown to be important in previous studies.[16] Therefore, it is impossible to determine the extent to which the Nyquist limit/color filter change actually affects jet size due to the necessary damping of the effect imposed by the increased frame rate. It is thus possible that the observed effects in this study could be much greater had the frame rate been held constant. This fact at least tends to confirm the validity of the results, because the increased frame rates would predispose the jets to become larger.

The most obvious instrument setting that affects jet size is gain. Gain was not studied here because it is simply the amplification of the basic signal. Higher gain settings tend to produce larger jet images, and with further increases in gain, noise will ultimately appear outside the jet. In most centers, gain is adjusted to produce maximal jet size just below the level at which noise appears. Gain is generally not annotated on the Doppler screen, and if so, it is usually not in a quantitative manner (in terms of decibels) but rather just given as a numerical value indicating the level within the available range on that instrument. In summary, up to the level of noise, variable gain settings may produce variable changes in the size of the jet, and our only recommendation is to advise a consistent method of setting gain within a clinic until instruments are further standardized.

The results of this study clearly show that jet areas are not reproducible from instrument to instrument when flow is held constant. There are two practical reasons for this result. First, as shown by the tables, it is virtually impossible to obtain identical settings because of the array of automatic changes and choices available for a given instrument. Second, even when settings are reasonably close, such as the Hewlett Packard 1000 0.26-m/s Nyquist limit and the Ultramark 9 0.27-m/s Nyquist limit, a clear difference in color Doppler flow area is noted (18.44 cm^2 for the Ultramark 9 compared with 13.6 cm^2 for the Hewlett Packard 1000). The lower frame rate (6.1 Hz for the Ultramark 9) suggests that it is smaller, but instead a significant difference in the opposite direction was observed.

With the increased attention toward transesophageal echocardiography, all the results presented here were intentionally obtained using a transesophageal probe.

These studies clearly indicate the tremendous variability resulting from instrument setting variation on color Doppler instruments. Because of arbitrarily defined instrument settings, it is difficult to make quantitative comparisons between different instruments since the exact algorithms used to display the basic Doppler data are unavailable to the user.

This point is highlighted by the color filter results. In the most basic sense, color filter settings define the jet boundary. Velocities above this high-pass filter (or low-velocity reject) are displayed in color, and those below are not. However, in practice, color filter settings

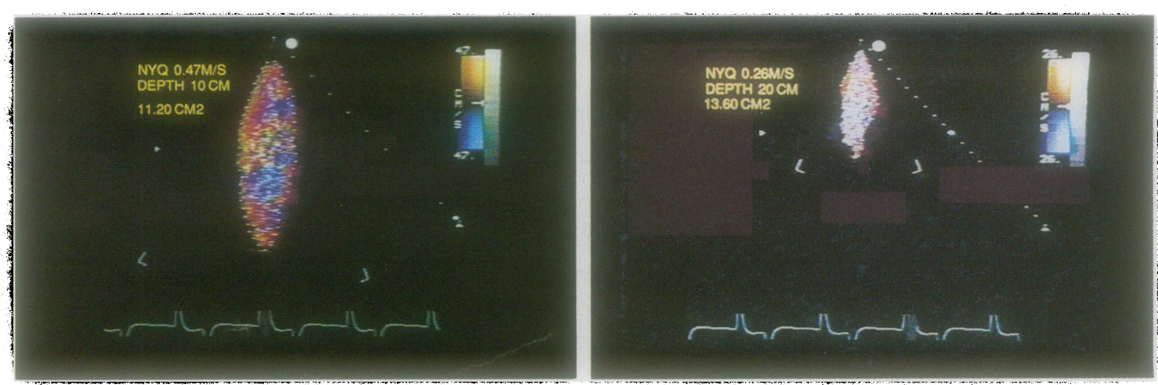

Fig 5. Effect of Nyquist limit (NYL) on image depth and color Doppler area (CDA) (Hewlett Packard 1000). A change in NYL from 0.47 m/s (A) to 0.26 m/s (B) results in simultaneous alteration of the image depth from 10 cm to 20 cm. Note that the CDA also increases from 11.20 cm^2 (A) to 13.60 cm^2 (B). Other parameters, such as color filter and peak flow velocity, were kept constant.

TABLE 6. Effect of Changes in Nyquist Limit on Color Doppler Flow Areas at Sector Angles 45° and 90° (Hewlett Packard 1000)

	45° Sector Angle				90° Sector Angle			
	0.26 m/s NYL	0.32 m/s NYL	0.40 m/s NYL	0.47 m/s NYL	0.26 m/s NYL	0.32 m/s NYL	0.40 m/s NYL	0.47 m/s NYL
Depth, cm	20	16	12	10	20	16	12	10
FR, Hz	10	11	13	15	6	8	8	10
CDA, cm²	13.6	13.4	11.9	11.2	13.4	13.4	11.9	10.1
CDA, % change	0	−1.5	−12.5	−17.7	0	0	−11.2	−24.7
	P<.001				*P*<.001			

NYL indicates Nyquist limit; FR, frame rate; and CDA, color Doppler flow area.
Peak flow velocity was 0.8 m/s, and color filters were low.

are not sharp-edged filters but rather gradually sloped ones. Manufacturers may annotate an "effective" color filter on the screen, which would apply to the average filter, but the steepness of the filter (Fig 2) can significantly affect jet appearance.

In either case, although color filters were originally used to eliminate high-amplitude, low-frequency signals from cardiac structures, it has also been clear that they would act as a velocity filter, which in effect defines the boundary of the jet. (On the Vingmed unit studied here, the filter setting is labeled as "low-velocity reject.") It is of concern that serial studies are performed without annotation or control of color filter settings when these settings define the jet boundary and therefore the area.

These results also point out the importance of annotating instrument settings (within a single machine) for the same patient who might undergo serial examinations. Jet planimetry methods can be greatly affected by variations in jet area because of instrument settings, even if physical flow through the regurgitant orifice remains constant.

Because the observed differences between instruments depend largely on proprietary data-processing algorithms, only two partial solutions to this problem can be offered at the present time. (1) The most intuitive is for each laboratory to carefully record all of the relevant instrument settings and retune the instrument to these settings for subsequent examinations of the same patient. Following this procedure for all relevant settings will require a commitment to slight increases in echo examination times and demonstration of the importance of these concepts to the technician. (2) A more ambitious approach involves a process of standardization in which manufacturers agree to participate in a study using single patients with specific color maps designed for matching relevant settings between instruments.

Study Limitations

The flow model chosen for this study is clearly simplified. Jets that occur in vivo issue into compliant chambers of variable size. They may also impinge on adjacent or distal walls to varying extents depending on chamber geometry and lesion configuration, and this may obscure the accurate assessment of such jets. Respiratory interference, obesity, and other sources of poor acoustic windows may degrade the quality of the color Doppler image of an echocardiographic evaluation. The degree of regurgitation may also be variable during different phases of the cardiac cycle.

However, by creating the simplified central pulsatile jets studied here, we have eliminated these compounding factors intentionally to isolate the effects of instrument parameters in the transesophageal application.

As stated, a clear limitation of the study was the inability to compare exact setting combinations between instruments. Unfortunately, because of a lack of standardization, the comparisons we made were as close as could be achieved. We note that variability between instruments due to the fact that identical settings cannot be achieved is in itself a critical issue.

Conclusions

In summary, factors affecting jet size include instrument settings within a given instrument and physical factors affecting distal jet behavior for constant orifice

TABLE 7. Effects of Changes in Nyquist Limit on Color Doppler Flow Areas for Sector Angles 45° and 90° (Advanced Technology Laboratories Ultramark 9)

	45° Sector Angle				90° Sector Angle			
	0.27 m/s NYL	0.31 m/s NYL	0.35 m/s NYL	0.39 m/s NYL	0.27 m/s NYL	0.31 m/s NYL	0.35 m/s NYL	0.39 m/s NYL
FR, Hz	6.1	6.9	7.6	8.3	3.7	4.2	4.6	5.1
CDA, cm²	18.44	16.22	15.1	14.1	16.21	14.1	13.83	13.23
CDA, % change	0	−12.0	−18.1	−23.5	0	−13.0	−14.7	−19.4
	P<.001				*P*<.001			

NYL indicates Nyquist limit; FR, frame rate; and CDA, color Doppler flow area.
Peak flow velocity was 0.8 m/s, color filters were low, depth was 13 cm, and color filters were 200 Hz.

Table 8. Effect of Change in Color Filter on Color Doppler Flow Area for Sector Angles 45° and 90° (Advanced Technology Laboratories Ultramark 9)

	45° Sector Angle (FR=3.7 Hz)			90° Sector Angle (FR=6.1 Hz)		
	400 Hz CF	600 Hz CF	800 Hz CF	400 Hz CF	600 Hz CF	800 Hz CF
CDA, cm^2	13.31	13.12	11.39	14.12	12.52	10.93
CDA, % decrease	0	1.5	14.4	0	11.3	22.6
		P=.001			P<.001	

CF indicates color filters; CDA, color Doppler flow area; and FR, frame rate.
Flow velocity was 0.8 m/s, Nyquist limit was 0.27 m/s, and depth was 13 cm.

Table 9. Effect of Changes of Nyquist Limit on Color Doppler Flow Area for Sector Angles 45° and 90° (Toshiba 160A)

	45° Sector Angle				90° Sector Angle			
	0.23 m/s NYL	0.31 m/s NYL	0.39 m/s NYL	0.42 m/s NYL	0.23 m/s NYL	0.31 m/s NYL	0.39 m/s NYL	0.42 m/s NYL
FR, Hz	14.0	9.0	12.0	13.0	10.0	9.0	12.0	13.0
CDA, cm^2	13.77	10.20	9.06	7.54	12.6	10.4	9.5	9.2
CDA, % change	0	−25.9	−34.2	−55.3	0	−17.5	−24.6	−17.0
			P<.001				P<.001	

NYL indicates Nyquist limit; FR, frame rate; and CDA, color Doppler flow area.
Peak flow velocity was 0.8 m/s, color filters were 360 Hz, and depth was 12 cm.

Table 10. Effects of Changes in Frame Rate on Color Doppler Flow Area for Sector Angles 45° and 90° (Toshiba 160A)

	45° Sector Angle					90° Sector Angle		
	5.0 Hz FR	8.0 Hz FR	10.0 Hz FR	14.0 Hz FR	18.0 Hz FR	5.0 Hz FR	7.0 Hz FR	10.0 Hz FR
CDA, cm^2	9.06	10.33	10.37	13.77	13.4	12.2	11.6	12.6
CDA, % change	0	+14.0	+14.5	+52.0	+47.9	0	−4.9	+3.3
			P<.001				P=.114	

FR indicates frame rate; and CDA, color Doppler flow area.
Peak flow velocity was 0.8 m/s, Nyquist limit was 0.23 m/s, depth was 12 cm, and color filters were 360 Hz.

flows. Such physical factors could be surrounding orifice geometry, wall impingement and reflection of the flow, and cardiac flow signal variability. If all of these factors are controlled and useful methods are derived for a single machine, new thresholds of severity must be defined for new instruments entering a clinical setting. Although new quantitative techniques using the principle of conservation of mass or momentum have shown initial success, it is likely that jet size will continue to be used in the clinical setup, at least as a qualitative marker of the severity of regurgitation. The thresholds defined from our laboratory[11] are rigidly applied in some clinics, but in many others, jet size is viewed more qualitatively.[15] In either case, the growing number of factors that produce variability in jet size for constant degrees of flow must be kept in mind by the clinical echocardiographer. Therefore, the clinical implications of this study are that the echocardiographer should use a single instrument on a particular patient and that each time a follow-up examination is done, care should be exercised to ensure it is performed under identical equipment settings. Furthermore, the instrument should be validated regularly by an engineer to assess and confirm the proper operation and verification of the electronics of the instrument. Also, the proper operation of the instrument should be verified with a phantom in simple flow experiments under well-controlled conditions. For identical flows and instrument settings, the jet size should not change. Temporal deterioration of the transducer will be manifested with jet size variability.

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