JACC Vol. 8, No. 5
November 1986:1047–58

METHODS

Patterns and Timing of Doppler-Detected Intracavitary and Aortic Flow in Hypertrophic Cardiomyopathy

PAUL G. YOCK, MD, LIV HATLE, MD,* RICHARD L. POPP, MD, FACC

Stanford, California and Trondheim, Norway

This study describes the velocity characteristics of left ventricular and aortic outflow in 25 patients with hypertrophic "obstructive" cardiomyopathy. Systematic pulsed and continuous wave Doppler analysis combined with phonocardiography and M-mode echocardiography was used to establish the pattern and timing of outflow in the basal and provoked states. This analysis suggests that 1) the high velocity left ventricular outflow jet can be reliably discriminated from both aortic flow and the jet of mitral regurgitation using Doppler ultrasound; 2) the Doppler velocity contour responds in a characteristic fashion to provocative influences including extrasystole and Valsalva maneuver; 3) the onset of mitral regurgitation occurs well before detectable systolic anterior motion of the mitral valve; 4) left ventricular flow velocities are elevated at the onset of systolic anterior motion of the mitral valve, suggesting a significant contribution of the Venturi effect in displacing the leaflets and chordae; 5) the high velocities of the outflow jets are largely dissipated by the time flow reaches the aortic valve; and 6) late systolic flow in the ascending aorta is nonuniform, with formation of distinct eddies that may contribute to "preclosure" of the aortic valve.

(J Am Coll Cardiol 1986;8:1047–58)

The recent development of combined cardiac Doppler and two-dimensional echocardiography provides a new approach to the direct measurement and localization of abnormal outflow velocities in patients with hypertrophic cardiomyopathy and intracavitary pressure gradients. Previous Doppler studies in this group of patients concentrated on brachial, carotid and aortic flow signals and on the signals of mitral regurgitation. Gault (1) and Benchimol (2) and their coworkers originally reported the finding of early peak flow velocities in brachial artery Doppler recordings from patients with hypertrophic cardiomyopathy. Joyner et al. (3) described a distinctive biphasic velocity pattern in the carotid Doppler tracings from these patients. More recently, transcutaneous Doppler studies of aortic blood flow velocities (4–6) demonstrated that the aortic velocity contour in patients with hypertrophic cardiomyopathy and an outflow gradient has an early peak with a prolonged ejection phase. Doppler-detected mitral regurgitant flows were correlated with systolic anterior motion of the mitral valve by Kinoshita et al. (7), who used pulsed wave Doppler ultrasound to demonstrate disturbed flow in both the left atrium and the left ventricular outflow tract in patients with hypertrophic cardiomyopathy.

The first description of velocity patterns within the left ventricle by transcutaneous ultrasound was reported by Hatle and Angelsen (8), who analyzed pulsed and continuous wave tracings in selected patients. No previous investigation has attempted systematic pulsed and continuous wave Doppler velocity analysis of left ventricular outflow in a group of patients with hypertrophic cardiomyopathy.

The study group reported here consists of 25 patients with the echocardiographic diagnosis of hypertrophic cardiomyopathy who, in addition, had elevated systolic flow velocities by Doppler study within the left ventricle. The main purpose of our study was to attempt to characterize the patterns of left ventricular outflow and aortic velocities in this group. Cardiac catheterization was not performed in all patients, and correlation with direct pressure measurements is not presented here.

Methods

Study patients (Table 1). The study group consisted of 14 outpatients from the Regional Hospital, University of Trondheim and 11 patients from Stanford University Hospital. Patients were recruited for the study on the basis of

From the Cardiology Divisions of Stanford University School of Medicine, Stanford, California and *University of Trondheim, Trondheim, Norway. This work was supported in part by Grants T32-HL-07625 and 1-F32-HL-06827 from the National Institutes of Health, Bethesda, Maryland. Dr. Hatle was supported by a grant from the Norwegian Council of Cardiovascular Diseases, Oslo, Norway.

Manuscript received March 10, 1986; revised manuscript received May 28, 1986, accepted June 11, 1986.

Address for reprints: Richard L. Popp, MD, Cardiology Division, Stanford University Medical Center, Stanford, California 94305.

0735-1097/86/$3.50

Table 1. Patient Profiles and Flow Velocities*

Patient	Age (yr)	Drug	Rhythm	HR (beats/min)	Peak Flow Velocity (m/s)			Outflow Velocity at SAM (m/s)
					LV Outflow Tract	Aortic Leaflets	Ascending Aorta	
1	70	V	SB	46	3.8*	2.4	1.8	—
2	48	V	S	65	5.5*	2.0	0.9	1.8
3	68	V	S	66	2.6	2.1	1.6	1.4
4	68	V	S	54	2.7*	—	1.2	1.2
5	67	P,V	S	64	4.8*	1.9	1.3	2.4
6	60	V	S	65	3.8	2.0	1.6	0.8
7	58	V	S	60	2.7*	—	1.1	—
8	63	V	S	60	5.0	2.5	1.8	—
9	69	0	S	64	5.4	2.3	1.8	1.7
10	72	V	S	82	5.1*	2.2	1.9	—
11	60	V	S	66	4.2	2.2	1.4	1.6
12	67	D,P	S	58	5.5	—	1.6	1.6
13	64	0	S	64	4.0	—	1.4	1.2
14	31	P	S	56	4.2	2.3	1.4	1.4
15	67	At	S	57	3.2	2.3	0.9	1.4
16	42	P	S	62	5.2	2.7	—	2.2
17	59	Am	S	56	3.5	—	—	1.0
18	70	V	S	78	4.8*	2.1	0.8	2.6
19	54	0	S	73	3.2	—	—	1.4
20	65	DP	S	72	4.0	1.4	0.9	1.2
21	45	0	S	64	2.0	1.6	1.1	1.2
22	59	D,V	AF	58	3.2	2.0	1.4	—
23	65	P,V	AF	66	2.8	2.2	1.2	—
24	38	V	AF	68	5.1*	2.0	1.4	—
25	78	P,V	AF	64	5.4	—	1.7	—

*Tracings with high velocity dropout in Doppler signal amplitude (see text). Peak left ventricular outflow jet velocities are equal to or greater than the value listed. AF = atrial fibrillation; Am = amiodarone; At = atenolol; D = digoxin; DP = disopyramide; LV = left ventricular; P = propranolol; S = sinus; SB = sinus bradycardia; V = verapamil; 0 = no medication; — = equal unclear recording of flow velocity at this position. Velocities during systolic anterior motion (SAM) of the mitral valve (last column) were measured only in those cases in which the onset of this motion was well defined on the M-mode recording.

two-dimensional echocardiographic findings typical of hypertrophic cardiomyopathy and Doppler studies that showed elevated systolic velocities in the left ventricle (>1.1 m/s) (9). Septal thickness at end-diastole ranged from 1.6 to 2.8 cm (mean 2.2), left ventricular posterior wall thickness ranged from 0.8 to 2.8 cm (mean 1.3) and septal/posterior wall ratios ranged from 1.0 to 2.6 (mean 1.8). All 25 patients had systolic anterior motion of the mitral valve; in 4 of these, this finding could not be recorded in the M-mode parasternal view because of poor quality images, but was seen on two-dimensional apical views. One patient in the series demonstrated prominent apical hypertrophy in addition to septal hypertrophy by two-dimensional echocardiography.

Twenty-one of the 25 patients had sinus rhythm. The remaining four patients with atrial fibrillation were included for purposes of qualitative analysis of Doppler outflow patterns; timing correlations with the M-mode echocardiogram and phonocardiogram were not performed in these four patients. Four of the 14 patients from Trondheim and all 11 of the patients from Stanford had previous cardiac catheterization documenting an abnormal intracavitary left ventricular pressure gradient, either at rest or with provocation by extrasystole or Valsalva maneuver, or both. Medications at the time of the Doppler examination included verapamil (15 of 25) and beta-blocking agents (8 of 25); 4 of the patients were receiving no medications (Table 1).

Echocardiography. Doppler echocardiographic recordings were made using Irex Exemplar and System IIIB ultrasonographs. Two-dimensional and M-mode studies were obtained in each patient from the conventional views. Doppler examinations were performed using both continuous and pulsed wave modes. Flow velocities across the aortic valve were recorded from the apex and the suprasternal notch. In most cases, flow velocities from the ascending aorta could be recorded from the suprasternal notch only. Left ventricular outflow signals were obtained from the apex and the suprasternal notch when possible. Mitral regurgitation signals were recorded from the apical and parasternal long-axis views. In the 11 patients from Stanford, the Val-

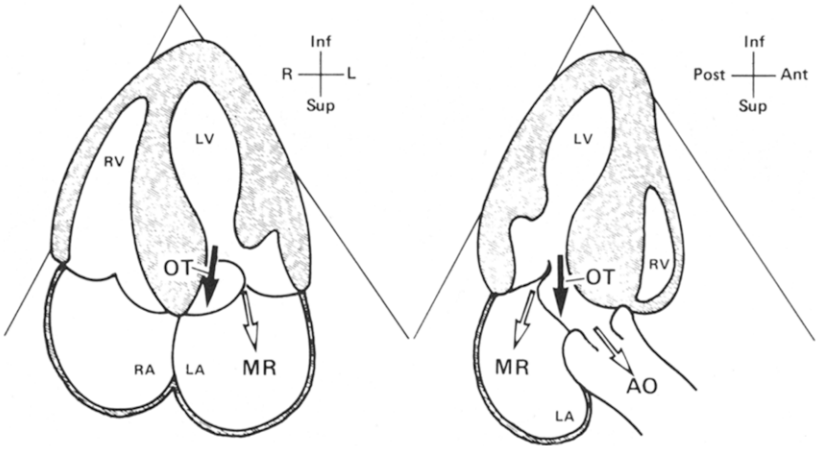


Figure 1. Echocardiographic views showing the direction of the left ventricular outflow tract (OT) jet indicated by **closed arrows**, compared with aortic outflow (AO) and mitral regurgitation (MR) jet shown by **open arrows**. **Left panel**, Apical four-chamber orientation. **Right panel**, Apical long-axis orientation. Ant = anterior; Inf = inferior; L = left; LA = left atrium; LV = left ventricle; Post = posterior; R = right; RA = right atrium; RV = right ventricle; Sup = superior.

salva or amyl nitrite provocation maneuvers, or both, were performed. Phonocardiograms were recorded along the left sternal border at the area where the outflow murmur was loudest by auscultation.

Temporal correlations between Doppler tracings and M-mode echocardiograms were made by superimposing QRS complexes from simultaneous electrocardiograms. Phonocardiograms were obtained simultaneously with Doppler and M-mode recordings. Intervals from three successive beats in sinus rhythm with identical RR intervals were measured and an average interval calculated.

Results

Ventricular outflow velocities. Maximal left ventricular outflow velocities by continuous wave Doppler study ranged from 2.0 to 5.5 m/s (mean 4.1). Precise transducer positioning and angulation were critical in obtaining optimal spectral contours in the outflow jet recordings. The sensitivity to beam orientation was similar to that in cases of aortic stenosis, and suggests that the outflow jet in hypertrophic cardiomyopathy is relatively narrow, like the aortic stenosis jet. The outflow jet was optimally recorded with the ultrasound beam directed midway between the axes of mitral inflow and aortic outflow (Fig. 1). Thus the outflow jet was not directed toward the aortic leaflets, but along an axis that was posterior and lateral (leftward) relative to the aortic anulus. When the transducer beam was angled more anteriorly, velocity recordings could be obtained from the level of the aortic valve. These flow velocity signals were often mixed with valve fluttering. In the majority of patients, signals from above the aortic valve could not be recorded from an apical transducer position. This contrasts with the situation in normal subjects, and may reflect the relatively acute angle between the outflow tract and aorta in hypertrophic cardiomyopathy. Suprasternal recordings gave good quality Doppler signals from the ascending aorta in all cases. In some patients, the outflow tract jet could also be recorded from the suprasternal notch by moving the beam slightly to the left of the ascending aorta position.

Velocity contour of left ventricular outflow tract jet. In addition to abnormally high velocities, the outflow jet

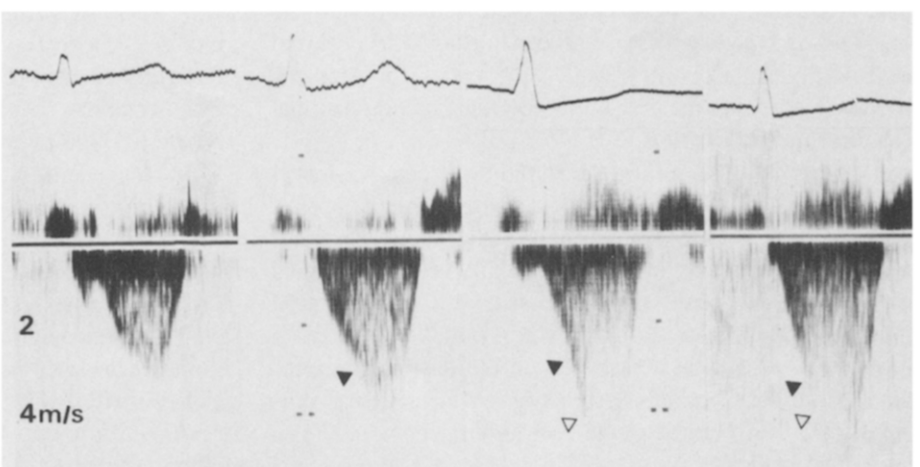


Figure 2. Four examples of left ventricular outflow tract jets recorded by continuous wave Doppler ultrasound. Velocities range from 3.4 to 5.5 m/s. The increasing slope as the jets accelerate toward peak velocities (**solid arrows**) is typical for left ventricular outflow signals in hypertrophic cardiomyopathy. At the highest velocities, there is often some decrease in signal intensity or amplitude (**open arrows**).

signals in our series demonstrated two characteristic features. 1) In the majority of cases with outflow tract velocities greater than 3 m/s, a gradual increase in velocity in the first portion of systole gave way to a more rapid increase (dV/dt) as the jet approached maximal velocity (Fig. 2, solid arrows). This gave a characteristic concave leftward appearance to the velocity curve of the outflow jet, which is not usually seen in the high velocity jet of aortic stenosis or mitral regurgitation. 2) A decrease in overall intensity or amplitude of the Doppler outflow tract signal commonly occurred before peak jet velocity was achieved, as reflected by the lighter portion in the spectral display on some beats in Figure 2 (open arrows). In some cases, this decrease in signal intensity was so significant that the highest velocity portion of the jet could not be clearly resolved. The decrease in intensity most likely represents a diminished number of red cell targets moving at these high velocities, and is consistent with decreased overall flow during this part of ejection (see Discussion). Thus, the Doppler signals suggest the presence of a high velocity but low volume flow jet in mid- to late systole. In all cases in our series, the Doppler left ventricular outflow signal continued throughout systole to the point of aortic valve closure as indicated on the simultaneous phonocardiogram or the Doppler recording itself.

The timing of the peak velocity of the outflow jet correlated with more familiar events associated with ventricular dynamics in hypertrophic cardiomyopathy. Comparison of the timing of peak velocity with the peak murmur intensity recorded by phonocardiogram showed variable correspondence, with a mean interval of 32 ms (range 0 to 70) (Fig. 3).

The timing of systolic anterior motion of the mitral valve was also analyzed relative to the Doppler outflow velocity (Table 2). By the time systolic anterior motion was first detectable on the M-mode recording, velocity of flow in the outflow tract was already clearly elevated, with a mean of 1.5 m/s in our series. Maximal anterior displacement of the mitral valve was accompanied by the highest outflow jet velocities; the average interval between maximal systolic anterior motion and peak outflow velocities was only 30 ms. Thus, the abrupt increase in velocities (dV/dt) occurred at a time when the mitral leaflet was encroaching on the septum, narrowing the area of outflow (just before maximal systolic anterior motion).

For the Stanford series, the duration of anterior mitral leaflet/septal contact on M-mode recording was compared with the peak outflow velocity in the eight patients whose M-mode tracings were of sufficient quality for unambiguous measurement. A positive correlation ($r = 0.6$) was noted between outflow velocity and the mitral leaflet/septal contact interval, as would be anticipated on the basis of the previously published relation (10) between the pressure gradient in the left ventricle and the duration of mitral leaflet/septal contact.

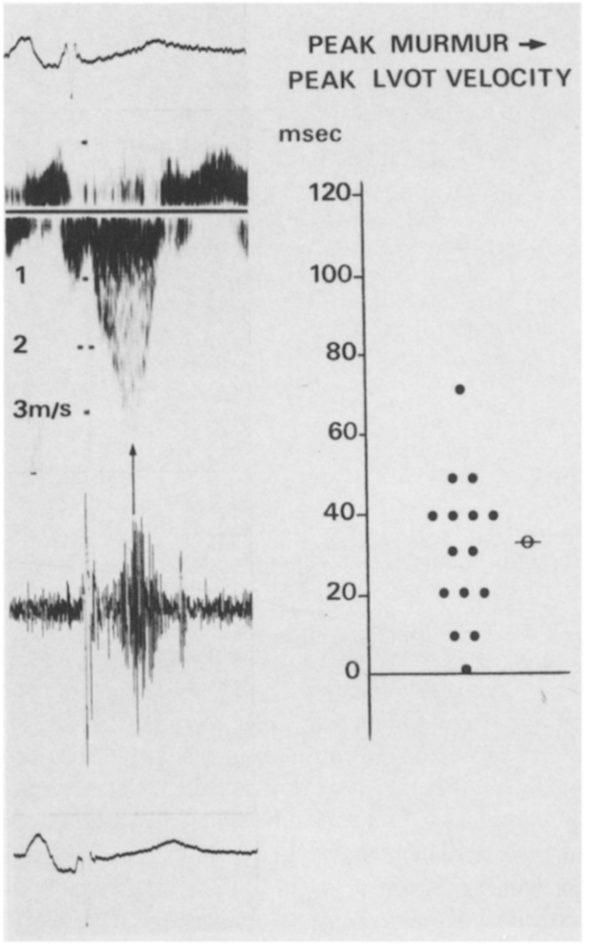


Figure 3. Correlation of continuous wave Doppler left ventricular outflow tract (LVOT) signal (**top**) with phonocardiogram (**bottom**). In the 15 patients with high quality Doppler and phonographic tracings, the peak velocities occurred a mean of 30 ms later than the maximal intensity murmur, with a range of 0 to 70 ms (**right panel**).

The velocity contour recorded at the level of the aortic valve demonstrated an early peak compared with normal outflow. Maximal velocities were markedly less than the left ventricular outflow jet velocities (Table 2). In the ascending aorta, velocity profiles were variable, depending on the position of the Doppler sample volume (see Discussion). In general, above the level of the aortic valve, the velocity peaked earlier than at the level of the anulus. Peak aortic outflow velocity occurred well before the peak left ventricular outflow tract velocity in all cases (Table 2, Fig. 4). Aortic valve leaflet partial closure ("preclosure") generally occurred at or closely after peak left ventricular outflow tract velocity.

Separation of left ventricular outflow tract and mitral regurgitation jets. Clear continuous wave Doppler signals of mitral regurgitation were recorded in 23 of the 25 patients.

Table 2. Timing of Systolic Events (in ms, relative to initial QRS deflection)*

Patient	Onset of MR	Onset of LV Ejection	Peak LVOT Jet Velocity	Peak Aortic Flow Velocity	Onset of SAM	Maximal SAM	Aortic Preclosure
1	40	110	340	190	—	—	—
2	90	110	240	160	140	240	240
3	30	100	270	190	90	240	—
4	90	120	300	260	100	220	—
5	70	110	350	210	180	320	—
6	70	120	240	210	120	270	—
7	80	140	270	220	—	250	280
8	80	120	280	220	—	280	—
9	70	120	310	180	140	250	250
10	70	90	240	170	—	—	—
11	60	90	320	180	110	240	—
12	70	120	300	270	160	300	390
13	70	120	340	250	160	290	290
14	60	90	280	180	160	240	—
15	80	150	320	170	150	240	—
16	90	130	340	—	180	260	270
17	60	120	300	—	100	270	280
18	60	80	290	170	140	200	—
19	—	100	260	—	110	260	—
20	10	100	220	170	120	250	290
21	80	120	370	230	160	270	—

*Patients 22 to 25 were not analyzed for timing because of atrial fibrillation. LVOT = left ventricular outflow tract; other abbreviations in Table 1.

In all but one patient, the onset of regurgitation was coincident with or immediately followed the first heart sound, and was well before the onset of the left ventricular outflow tract jet signal or systolic anterior motion (Table 2, Fig. 5). The onset of mitral regurgitation thus occurred significantly earlier than systolic anterior motion, as judged from the M-mode echocardiogram. In one patient with atrial fibrillation, the mitral regurgitation jet could be recorded only in late systole.

The left ventricular outflow tract and mitral regurgitation jets were both high velocity signals, directed away from the transducer and separated by as little as 1 cm at their origin. Distinguishing between the two jets required attention to several features of timing and contour: 1) the upstroke of the left ventricular outflow tract velocity signal was less abrupt, and typically showed a terminal acceleration curve (increased dV/dt); 2) the peak velocity of the mitral regurgitation jet was greater than that of the left ventricular outflow tract jet (reflecting the greater left ventricular/left atrial pressure gradient as compared with the left ventricular/aortic gradient); and 3) as mentioned, the onset of the left ventricular outflow tract jet was delayed relative to the onset of mitral regurgitation. It was frequently possible to record both jets from the same beam position (Fig. 5).

Pulsed wave mapping provided a reliable check on whether a given continuous wave signal represented the left ventricular outflow jet or mitral regurgitation. By maintaining a steady transducer position and switching from continuous to pulsed mode, the location of the jet could be clearly established (mitral regurgitation mapped in the left atrium, and left ventricular outflow tract jet in the left ventricle).

Provocative maneuvers. Eleven patients in this study underwent provocation with the Valsalva maneuver or amyl nitrite inhalation, or both, in an attempt to define the effect on jet velocities. With the Valsalva maneuver, the left ventricular outflow tract signal was generally lost or diminished in amplitude during strain (phase II) because of interference from lung or change in transducer position relative to the outflow tract, or both (Fig. 6a). However, the beats immediately after release were generally easily imaged, and showed increased velocities consistent with an increase in pressure gradient. Amyl nitrite inhalation was equally effective in provoking an increased pressure gradient and outflow jet velocity. Continuous imaging of the jet was achieved by asking the patient to suspend respiration for a brief period after inhalation of the amyl nitrite. Postextrasystolic accentuation of outflow tract velocities was clearly recorded in patients who presented with an irregular rhythm (Fig. 6b).

Pulsed wave localization of jet velocities. Mapping of outflow velocities using pulsed wave Doppler ultrasound revealed a consistent pattern of flow acceleration in the left ventricle (Fig. 7), which can be divided into four levels based on the Doppler characteristics. The anatomic region where these flow patterns occur can be located approximately by means of simultaneous two-dimensional imaging. However, movement of the heart relative to the Doppler

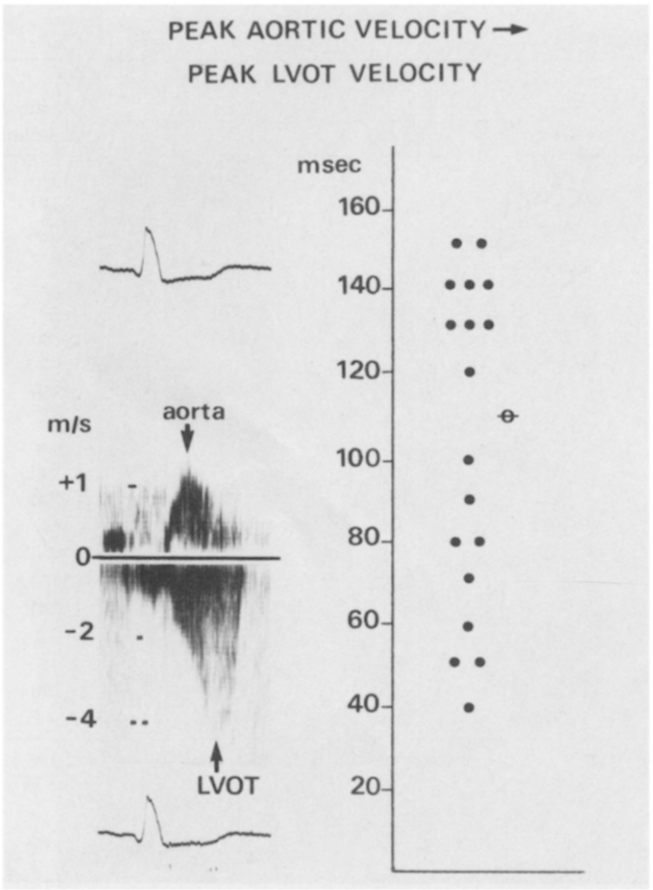


Figure 4. Timing of aortic versus left ventricular outflow velocities. Continuous wave tracings from the aorta and left ventricular outflow tract (LVOT) of beats with identical RR intervals were superimposed by means of simultaneous electrocardiograms. In all cases where a discrete maximum could be assigned to both signals, the aortic velocities peaked earlier than the outflow velocities (**right panel**).

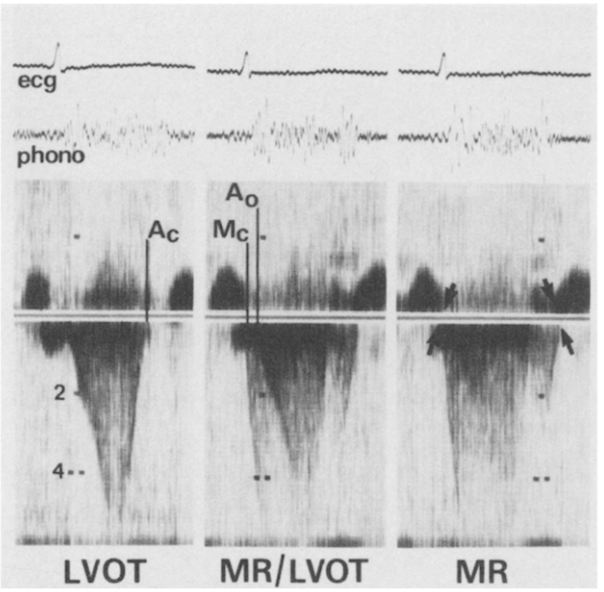


Figure 5. Recordings showing separation of continuous wave Doppler signals from the left ventricular outflow tract (LVOT) jet and the mitral regurgitation (MR) jet. The panel on the **left** is a recording of the outflow jet alone, with velocity calibrations in meters per second. The panel on the **right** shows the mitral regurgitation jet, with temporal continuity between mitral inflow (above the baseline) and mitral regurgitation (below the baseline) indicated by the **arrows**. The **middle panel** shows the overlapping outflow/mitral regurgitation signal obtained with the beam in an intermediate position. A_c = aortic closure; A_o = aortic opening; M_c = mitral closure.

sample volume precludes exact anatomic localization in a given case. Starting with the sample volume at the left ventricular apex and moving toward the base, the first characteristic velocity contour was encountered in the region of the base of the papillary muscles (Fig. 7, position 1). Here, maximal velocities ranged from 0.4 to 1.7 m/s; at this level there was typically a sharp peak in the velocity occurring at end-systole. In the one case in our series with prominent apical as well as septal hypertrophy, these late systolic velocities were considerably higher at position 1, reaching 3.6 m/s. This was compatible with the marked chamber narrowing seen at the apex on the two-dimensional image.

Slightly farther from the apex, at the level of the papillary muscle tips, somewhat higher velocities were recorded with a rounder, earlier peak (Fig. 7, position 2). This represents the level where flow begins to accelerate to form the left ventricular outflow tract jet. The jet itself was most typically localized beginning at the level of the chordae/mitral leaflet tips (Fig. 7, position 3). Here, a definite increase in velocities was detected, usually accompanied by aliasing of the pulsed wave signal. The highest jet velocities were recorded a short distance beyond this level (Fig. 7, position 4), but could only be tracked for a distance of 1 to 2 cm. Beyond this level, an anterior shift of the beam was generally necessary to record flow higher in the left ventricular outflow tract and across the aortic valve. Velocities in these regions were clearly lower than in positions 3 and 4 (Table 1).

Discussion

Doppler echocardiography in hypertrophic cardiomyopathy. This study represents a systematic attempt to use Doppler echocardiography to characterize the velocity profile of the outflow jet in patients with hypertrophic cardiomyopathy and elevated left ventricular velocities. Proper recording of the outflow jet requires a sensitive Doppler instrument with a high velocity capability. This may account for the difficulty Maron et al. (6) reported in detecting outflow jets with a pulsed wave system. Flow patterns in the outflow tract are relatively complicated in hypertrophic cardiomyopathy, and the left ventricular outflow tract signal

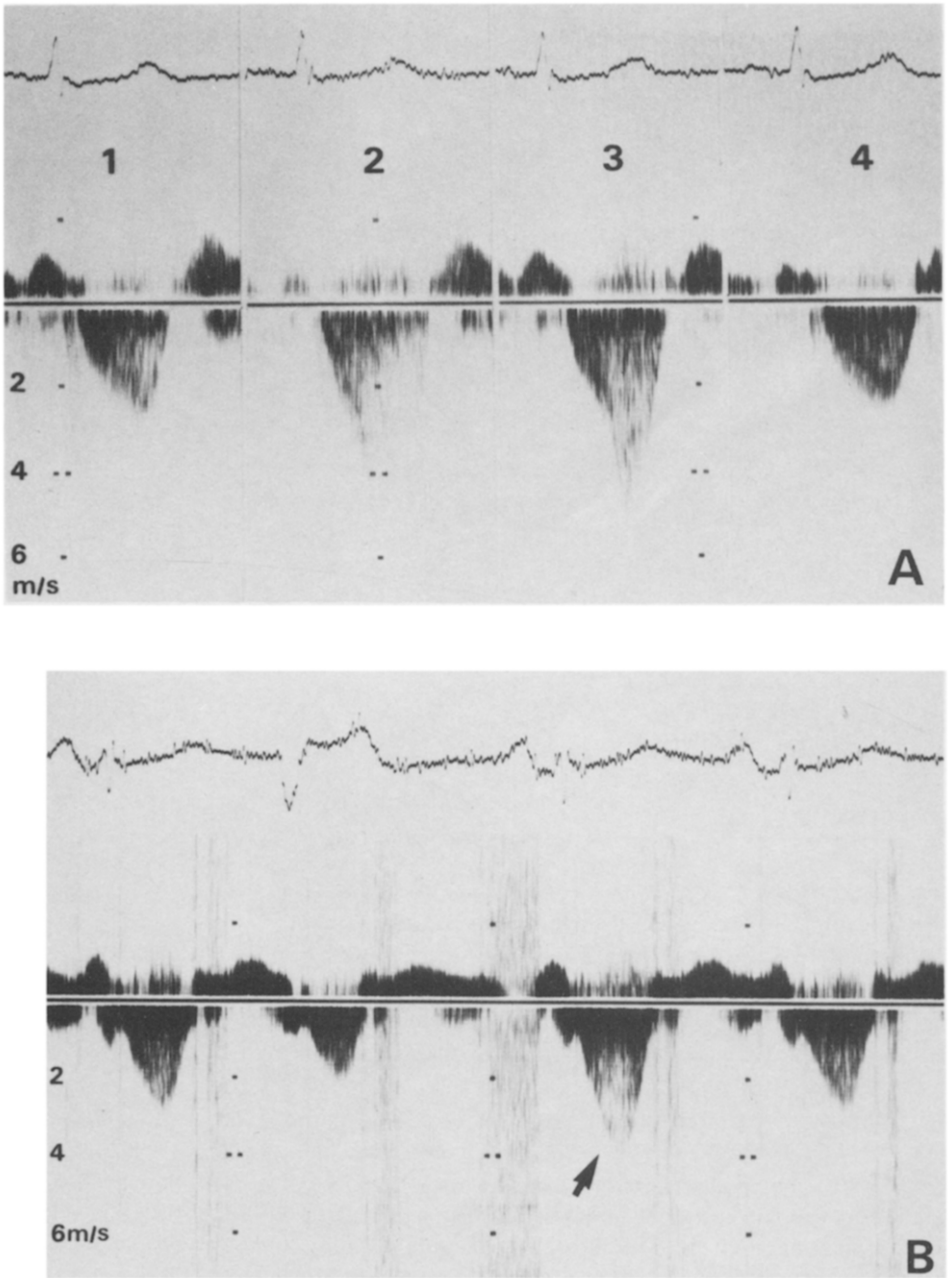


Figure 6. Continuous wave Doppler recordings of left ventricular outflow jets with provocative maneuvers. **A**, Valsalva maneuver. At basal conditions (1), the peak velocity is approximately 2.8 m/s. During the strain phase of the Valsalva maneuver, the signal is poorly recorded (2), but on the first beat after release, the velocity is seen to reach approximately 4.6 m/s (3). One minute after release, the velocity has returned to the baseline (4). **B**, Postextrasystolic potentiation. A premature ventricular contraction (second beat) is followed by an augmentation in the outflow tract velocity to approximately 4.0 m/s (**arrow**).

must be distinguished from those of mitral regurgitation and aortic outflow. Fortunately, with a significant gradient, the left ventricular outflow tract velocity contour is distinctive in most cases, with increasing slope (dV/dt) in mid-systole. Careful attention to this velocity contour, as well as mapping with pulsed wave Doppler ultrasound, allows discrimination of the outflow jet from the other neighboring flow signals.

The Doppler left ventricular outflow tract velocity contour responds in a characteristic fashion to provocative influences, including the Valsalva maneuver and extrasystole (Fig. 6.) Thus, Doppler ultrasound provides the ability to complement conventional echocardiography in the diagnosis of hypertrophic cardiomyopathy, as well as offering the potential to estimate intracavitary pressure gradients noninvasively using the Bernoulli equation, $\Delta P = 4V^2$ (where ΔP = the decrease in pressure in mm Hg and V = jet velocity in m/s) (11).

Left ventricular outflow tract jet orientation. Doppler ultrasound also provides a new and potentially powerful tool for analyzing the dynamics of flow in hypertrophic cardiomyopathy. One important observation from our data is that the high velocities of the left ventricular outflow tract jet

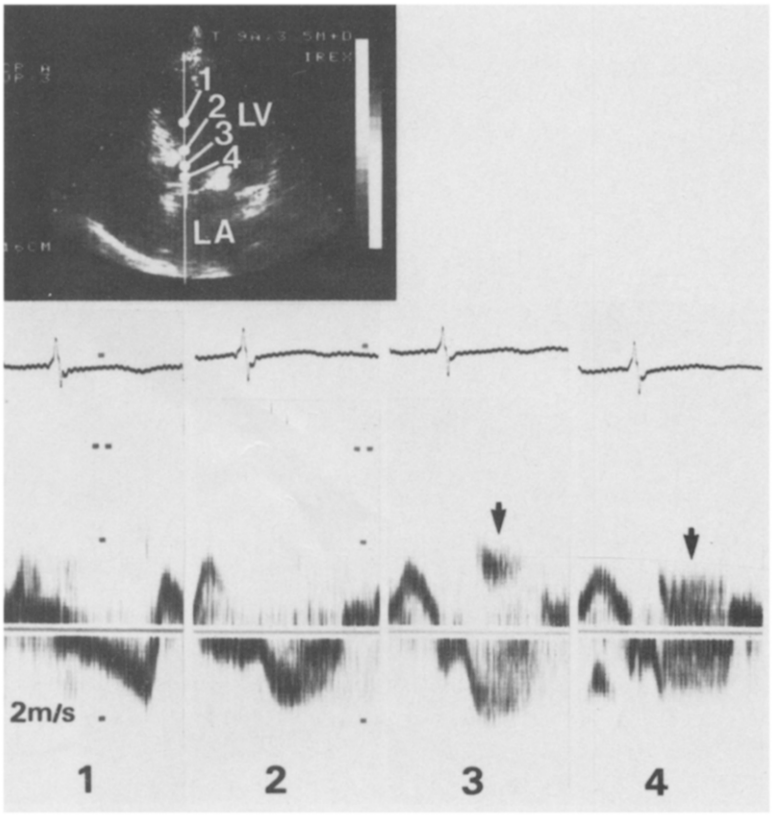


Figure 7. Pulsed wave mapping of left ventricular (LV) outflow jet from apical (1) to high outflow tract (4). The high velocities in the outflow tract cause signal aliasing (**arrows**). See text for details. LA = left atrium.

are generally not conducted to the aorta (average peak left ventricular outflow tract jet velocity 4.1 m/s compared with 1.4 m/s in the aorta) (Table 2). Direct data on the location and direction of the left ventricular outflow tract jet provided by Doppler ultrasound suggest two mechanisms for the dissipation in jet velocities in the high outflow tract: 1) The jet is formed a distance of 3 to 4 cm below the level of the aortic leaflets, as based on pulsed wave mapping. The combined influences of sheer, friction and boundary layer separation act to create disturbed flow and dissipation of energy, with progressive reduction in velocities of a jet as is seen, for example, in the jet of aortic stenosis (12). The relatively low volume of jet flow at the highest velocities may facilitate the effect of these forces in limiting the length of the jet. 2) The left ventricular outflow tract jet is directed posteriorly and laterally relative to the aortic anulus (Fig. 1). Thus, the jet is not aimed primarily through the leaflets, but instead is directed into the region of the posterior outflow tract below the aortic valve. Impact in the posterior outflow tract may contribute to disturbed flow, with dissipation of energy and the high velocities of the jet before flow reaches the ascending aorta.

Deceleration of outflow jets below the level of the aortic valve has been anticipated on the basis of pathologic studies. In cases of discrete subvalvular aortic stenosis, "jet lesions" may be seen on the ventricular surface of the aortic leaflets, suggesting the presence of a high velocity jet at the level of the valve in these cases. Comparable jet lesions are not found on the leaflets of patients with hypertrophic cardiomyopathy (13). The characteristic mural endocardial "plaque" located in the outflow tract of most patients with hypertrophic cardiomyopathy has been attributed to the combined effects of jet flow and mitral leaflet percussion from systolic anterior motion (13–15). Although the inferior (apical) margin of this plaque clearly mirrors the anterior mitral leaflet, fibrosis may extend up the outflow tract a distance of 2 to 4 cm, compatible with the extent of the jet as mapped by pulsed wave Doppler ultrasound (14,15).

Relation of left ventricular outflow velocities to systolic anterior motion. The mechanism of systolic anterior motion of the mitral valve (systolic anterior motion) has been attributed to a Venturi effect in the narrowed left ventricular outflow tract (16–18). Increased velocities in the region between the septum and anterior mitral leaflet create a zone of decreased pressure relative to the left ventricular chamber pressure present in the area posterior to the mitral apparatus. This pressure difference acts to lift the chordae tendineae and mitral leaflet tips anteriorly, further narrowing the outflow tract and increasing the velocity of outflow and the Venturi forces. The present study demonstrates that outflow velocities in the left ventricle are, in fact, elevated at the time systolic anterior motion is first seen on the M-mode

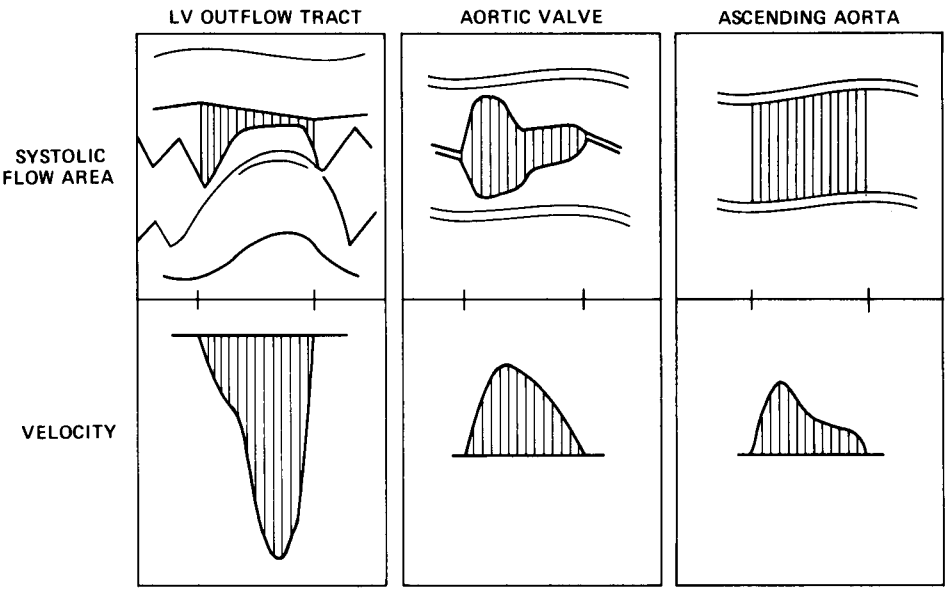


Figure 8. Illustration demonstrating flow area and velocity at the left ventricular (LV) outflow tract, aortic valve and ascending aorta. The cross-sectional area of flow is delineated by the M-mode echocardiogram (**top**). The Doppler velocity tracings (**bottom**) are shown in the orientation in which they are generally recorded: a negative velocity signal is obtained for the outflow jet from the apical transducer position; aortic signals are typically recorded from the suprasternal notch and are, accordingly, positive. Timing marks in each panel define the systolic ejection period (see text for discussion).

recording (Table 1), with a mean velocity of 1.5 m/s. These elevated velocities may be due to narrowing within the left ventricle or hyperkinetic contraction, or both. The fact that left ventricular outflow velocities at the level of the mitral leaflet are elevated at the onset of systolic anterior motion is compatible with a Venturi mechanism, but does not prove that this mechanism is responsible for systolic anterior motion. An abnormally brisk early contraction of the ventricle could produce increased velocities before some mechanical process (for example, papillary muscle contraction [19,20] or hyperkinetic posterior wall motion (21)) initiates systolic anterior motion of the mitral valve.

Jet velocity and systolic flow area. The Doppler velocity recordings at the various levels of the left ventricular outflow tract and aorta provide the basis for a comprehensive noninvasive description of the systolic flow events in hypertrophic cardiomyopathy. Theoretically, flow at any point in time can be calculated as the product of the cross-sectional area of flow and the Doppler-determined velocity: flow = area × average velocity (where "average velocity" refers to the spatial average). According to the "continuity equation" of fluid dynamics (22), net flow must be the same at each point in the outflow tract and aorta at any given time during ejection. In theory, a dynamic outflow tract area could be calculated from the continuity equation using aortic area and the point by point ratio of left ventricular outflow velocity to aortic flow velocity at either the level of the mitral valve or the ascending aorta (left ventricular outflow tract area = aortic area × aortic flow velocity ÷ left ventricular outflow velocity). In practice, however, this measurement would be unreliable because of inhomogeneity in the aortic flow profile (see later) and difficulty in determining a precise aortic flow area either at the level of the leaflets or in the ascending aorta.

The concept of flow continuity does help explain the relation between flow area and velocity at different levels in the left ventricle and aorta in hypertrophic cardiomyopathy (Fig. 8). At the level of the outflow tract, the flow area narrows markedly during ejection as the septum and anterior mitral leaflet converge (Fig. 8, left panel). As this outflow tract narrowing progresses, the velocity of the jet increases markedly, corresponding to an increased intraventricular pressure gradient as dictated by the Bernoulli equation. The net flow through the outflow tract is a function of these two variables: decreasing flow area and increasing velocity.

The fact that net flow through the outflow tract actually diminishes in mid- and late systole, even in the presence of the high outflow velocities, is suggested by the aortic flow velocity recordings (Fig. 8, middle panel). At the level of the aortic leaflets, the peak in the velocity contour occurs considerably earlier than the peak of the left ventricular outflow tract jet (Table 2). Thus, at a time when the left ventricular outflow tract jet velocities are still increasing, aortic flow velocities and flow area are both decreasing, the latter indicated by partial closure of the aortic leaflets (Figs. 4 and 8, middle panel).

The cross-sectional area of the ascending aorta is relatively fixed, with a larger area compared with the aortic leaflet flow area. This results in a lower peak velocity for aortic flow, along with an earlier and more marked decrease in the velocity contour compared with the signal at the leaflets (Fig. 8, right panel). In addition, it is likely that the entry of the narrow aortic jet into the wider flow area of the ascending aorta leads to formation of eddies that complicate the flow profile in late systole (see below).

Inhomogeneity in aortic flow velocity profiles. Previous Doppler echocardiographic studies (4–6) of aortic blood flow have documented that the velocity contour in the as-

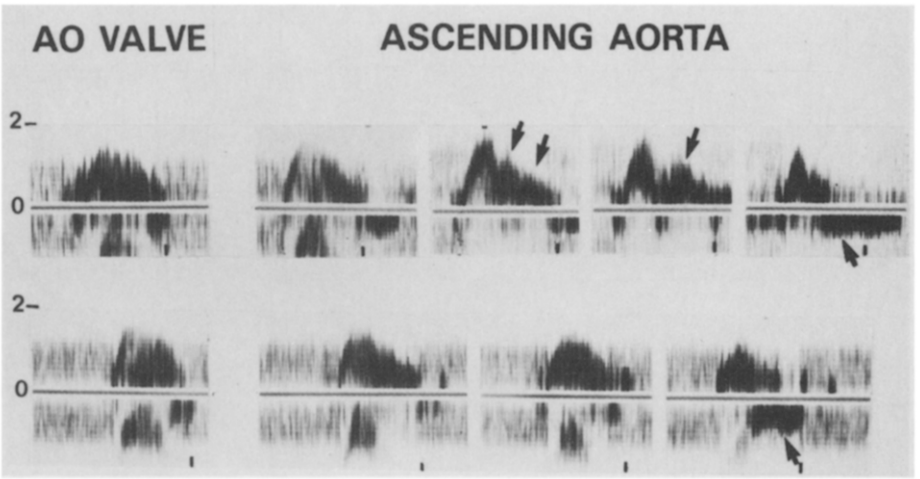


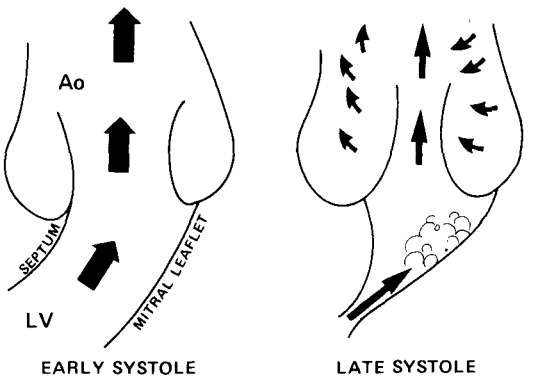
Figure 9. Examples from two patients (**top** and **bottom**) demonstrating the heterogeneity of pulsed wave velocity contours in the ascending aorta, and the change in contour relative to the signal at the level of the aortic (AO) leaflets. The single tracing on the **left** in each case is recorded at the level of the aortic valve; the remaining tracings are from different positions in the ascending aorta, 2 to 3 cm above the aortic leaflets. **Arrows** indicate secondary flow peaks (probable eddies), which may be either positive or negative. Marks at the bottom of each tracing designate timing of aortic closure recorded by the Doppler signal.

cending aorta peaks earlier in patients with hypertrophic cardiomyopathy than in normal subjects. What has not been evident from these studies is the high degree of heterogeneity in aortic velocity signals recorded at different sample volume positions in the ascending aorta in a given patient. Figure 9 shows representative tracings from two patients in our series. The velocity contour in late systole is highly variable, depending on the position of the sample volume in the aorta. In contrast to the study of Maron et al. (6), we did not find a second velocity peak to be a uniform feature of aortic flow velocity tracings in patients with hypertrophic cardiomyopathy and elevated outflow gradients. Although a "bifid" tracing with a second peak could be recorded in most of our patients at some position in the ascending aorta, moving the sample volume to different positions gave signals with single, double or triple positive peaks (Fig. 9, top panel). Signals with negative late systolic velocities were also encountered in most patients (Fig. 9, top and bottom). This high degree of heterogeneity in the velocity contours is strongly suggestive that late systolic eddies are formed in the aorta with different directions, depending on the location in the aorta. Each of the late velocity peaks probably represents a main eddy, which may be directed either towards or away from the transducer. An important implication of this finding is that the velocity recorded in mid- to late systole at any one position in the aorta does not necessarily reflect net flow in the aorta at that point in time. This may help explain the apparent discrepancy between transcutaneous Doppler studies demonstrating a prominent second late systolic velocity peak and invasive studies that have not shown a significant second peak in aortic flow (23–25). As Hernandez et al. (23) pointed out, the existence of a second peak in the aortic pressure pulse does not dictate an obligatory second peak in flow. The second pressure peak may be the result of reflected pressure waves after the forceful initial ejection, or a negative dip in the presssure because of rapid deceleration of blood.

The finding of prominent late systolic eddies in the ascending aorta is also consistent with aortic valve "preclosure" or partial closure. Bellhouse and Talbot (26) demonstrated that eddies created by deceleration of blood flow in the ascending aorta may help initiate aortic valve closure in normal subjects at a time when there is still forward flow through the valve. Therefore, aortic valve "preclosure" might be expected to occur in patients with hypertrophic cardiomyopathy as a result of a combination of early deceleration of flow and concomitant eddy formation in the ascending aorta.

Pathophysiologic implications. Figure 10 summarizes in schematic form some of the essential features of left ventricular outflow as demonstrated by Doppler velocity recordings. Early in systole, the outflow tract is open, and therefore relatively high flow is delivered into the aorta. In late systole, the outflow tract has narrowed, and a high velocity jet is formed, which is directed toward the posterior

Figure 10. Diagram summarizing the pattern of left ventricular (LV) outflow and aortic (Ao) flow velocities in hypertrophic cardiomyopathy. See text for details.



outflow tract, resulting in a region of disturbed flow. Much less flow is delivered to the aorta in late systole, flow area at the aortic leaflets is diminished and there is formation of eddies in the aorta, resulting in a complicated, inhomogeneous flow pattern and aortic valve "preclosure."

Some important conclusions concerning outflow dynamics follow from this velocity analysis. First, the Doppler studies clearly demonstrate that left ventricular and aortic flows continue throughout systole in patients with hypertrophic cardiomyopathy. This is compelling evidence against the concept that forward flow into the aorta ceases completely before the end of systole (25). It should be emphasized that Doppler ultrasound is extremely sensitive in detecting small amounts of volumetric flow; therefore the actual flow during late systole may be small, as has been suggested by invasive flow studies (19–21) and quantitative contrast and radionuclide angiography (24,25,27–30).

A second intriguing finding from the Doppler recordings in the majority of patients in this series is that mitral regurgitation was seen to begin at the onset of systole, coincident with the first heart sound. This argues against the position that mitral regurgitation is *initiated* as a result of contortion of the mitral apparatus associated with systolic anterior motion (31–33) or directly as a result of high left ventricular chamber pressures (34,35). These data do not allow differentiation between other postulated mechanisms for the initiation of mitral regurgitation, such as abnormal papillary muscle function in the context of hyperkinetic contraction (19) or mitral anular fibrosis and calcification. In our series, no clear relation was noted between the finding of prominent mitral anular reflections on the two-dimensional echocardiogram and the presence of a Doppler mitral regurgitation signal commencing with the first heart sound.

It is also important to emphasize that the data presented here do not address the issue of whether the degree of mitral regurgitation increases late in systole, that is, whether the largest portion of the regurgitant flow occurs after systolic anterior motion begins or during the high pressure phase of ejection. Current Doppler techniques are not accurate in assessing volumetric regurgitant flow as a function of time in systole. In some cases in our series, a clear increase in intensity of the mitral regurgitation signal was seen in mid- to late systole, suggesting an increased volume of red cell targets occurring after systolic anterior motion. However, this finding may not be reliable when the jet is moving relative to the ultrasound beam (as is probably the case with the mitral regurgitation jet in hypertrophic cardiomyopathy). Combined Doppler and two-dimensional echocardiography or "color flow" Doppler imaging may provide further insight into this problem.

Perhaps the single most important contribution of the Doppler velocity data in hypertrophic cardiomyopathy will be to provide new insight into the discussion concerning the role of outflow tract "obstruction" in this condition (36–42). Our series of patients with hypertrophic cardiomyopathy clearly demonstrates that as the outflow tract narrows in systole, a high velocity outflow jet is generated. The Bernoulli equation mandates that these increased jet velocities are accompanied by increased pressure gradients, as has been amply documented by direct pressure recordings. It should not be controversial to state, therefore, that in the left ventricle in hypertrophic cardiomyopathy, there is an abnormally high pressure gradient in systole associated with high velocity blood flow.

The critical pathophysiologic question is whether the elevated outflow tract gradient represents a significant stress to the ventricle and a stimulus for progressive hypertrophy. Doppler recordings of left ventricular outflow should provide further insight into this issue because the Doppler signals convey information about both the severity and duration of the high pressure phase. The combination of these data with noninvasive volume and flow determinations may allow estimation of ventricular work and stress variables under a variety of conditions. As this study emphasizes, however, extreme caution must be exercised in extrapolating from Doppler velocity signals to estimations of absolute flow, given the complexity of the flow pattern in this condition.

We thank Corrie Naasz and Steven Hill for their expert technical assistance, and Gretchen Houd for preparation of the manuscript.

References

1. Gault JH, Ross J, Mason D. Patterns of brachial arterial blood flow in conscious human subjects with and without cardiac dysfunction. Circulation 1966;34:833–48.
2. Benchimol A, Maia IG, Gartlan JL, Franklin D. Telemetry of arterial flow in man with a Doppler ultrasonic flowmeter. Am J Cardiol 1968;22:75–84.
3. Joyner CR, Harrison FS, Gruber JW. Diagnosis of hypertrophic subaortic stenosis with a Doppler velocity flow detector. Ann Intern Med 1971;74:692–6.
4. Boughner DR, Schuld RL, Persaud JA. Hypertrophic obstructive cardiomyopathy: assessment by echocardiographic and Doppler ultrasound techniques. Br Heart J 1975;37:917–23.
5. Gardin JM, Dabestani A, Glasgow GA, et al. Doppler aortic blood flow studies in obstructive and nonobstructive hypertrophic cardiomyopathy (abstr). Circulation 1982;66 (suppl II):II-267.
6. Maron BJ, Gottdiener JS, Arle J, Rosing DR, Wesley YE, Epstein SE. Dynamic subaortic obstruction in hypertrophic cardiomyopathy: analysis by pulsed Doppler echocardiography. J Am Coll Cardiol 1985;6:1–15.
7. Kinoshita N, Nimura Y, Okamoto M, Miyatake K, Nagata S, Sakakibara H. Mitral regurgitation in hypertrophic cardiomyopathy: noninvasive study by two-dimensional Doppler echocardiography. Br Heart J 1983;49:574–83.
8. Hatle L, Angelsen B. Pulsed and continuous wave Doppler in diagnosis and assessment of various heart lesion. In: Doppler Ultrasound in Cardiology. 2nd ed. Philadelphia: Lea & Febiger, 1985:205–16.
9. Hatle L, Angelsen B. Pulsed Doppler recording of intracardiac blood flow velocities: orientation and normal velocity patterns. In Ref 8:93.
10. Pollick C, Rakowski H, Wigle ED. Muscular subaortic stenosis: the quantitative relationship between systolic anterior motion and the pressure gradient. Circulation 1984;69:43–9.

11. Holen J, Aaslid R, Landmark K, Simonsen S. Determination of pressure gradient in mitral stenosis with a non-invasive ultrasound Doppler technique. Acta Med Scand 1976;199:455–60.
12. Goldberg SJ, Kececioglu-Draelos Z, Sahn DJ, Valdes-Cruz L, Allen H. Range gated echo-Doppler velocity and turbulence mapping in patients with aortic stenosis. Am Heart J 1982;103:858–63.
13. Roberts WC, Ferrans VJ. Pathologic anatomy of the cardiomyopathies. Hum Pathol 1975;6:306–23.
14. Davies MJ, Pomerance A, Teare RD. Pathologic features of hypertrophic obstructive cardiomyopathy. J Clin Pathol 1974;27:529–35.
15. Olsen ECJ. The pathology of idiopathic hypertrophic subaortic stenosis (hypertrophic cardiomyopathy): a critical review. Am Heart J 1980;100:553–62.
16. Wigle ED, Adelman AG, Silver MD. Pathophysiological considerations in muscular subaortic stenosis. In: Wolstenholme GEW, O'Connor M (eds). Hypertrophic Obstructive Cardiomyopathy. London: J & A Churchill, 1971:63–76.
17. Henry WL, Clark CE, Griffith JM, Epstein SE. Mechanism of left ventricular outflow obstruction in patients with obstructive asymmetric septal hypertrophy (idiopathic hypertrophic subaortic stenosis). Am J Cardiol 1975;35:337–45.
18. Pollick C, Morgan CD, Gilbert BW, Rakowski H, Wigle ED. Muscular subaortic stenosis; the temporal relationship between systolic anterior motion of the anterior mitral leaflet and the pressure gradient. Circulation 1982;66:1087–94.
19. Dinsmore RE, Sanders CA, Harthorne JW. Mitral valve regurgitation in idiopathic hypertrophic subaortic stenosis. N Engl J Med 1966;275:1225–8.
20. Simon AI, Ross J, Gault JH. Angiographic anatomy of the left ventricle and mitral valve in idiopathic hypertrophic subaortic stenosis. Circulation 1967;36:852–67.
21. Silverman KJ, Hutchins GM, Weiss JL, Moore GW. Catenoidal shape of the interventricular septum in idiopathic hypertrophic subaortic stenosis. Am J Cardiol 1982;49:27–32.
22. Fox RW, McDonald AT. Introduction to Fluid Mechanics. 2nd ed. New York: John Wiley, 1978:223.
23. Hernandez RR, Greenfield JC, McCall BW. Pressure-flow studies in hypertrophic subaortic stenosis. J Clin Invest 1964;43:401–7.
24. Pierce GE, Morrow AG, Braunwald E. Idiopathic hypertrophic subaortic stenosis: III. Intraoperative studies of the mechanism of obstruction and its hemodynamic consequences. Circulation 1964;30(suppl IV):IV-152–74.
25. Murgo JP, Alter BR, Dorethy JF, Altobelli SA, McGranahan GM. Dynamics of left ventricular ejection in obstructive and nonobstructive hypertrophic cardiomyopathy. J Clin Invest 1980;66:1369–82.
26. Bellhouse BJ, Talbot L. The fluid mechanics of the aortic valve. J Fluid Mech 1969;35:721–35.
27. Wilson WS, Criley JM, Ross RS. Dynamics of left ventricular emptying in hypertrophic subaortic stenosis: a cineangiographic and hemodynamic study. Am Heart J 1967;73:6–16.
28. Siegel RJ, Criley M. Comparison of ventricular emptying with and without a pressure gradient in patients with hypertrophic cardiomyopathy. Br Heart J 1985;53:283–91.
29. Sugrue DD, McKenna W, Dickie S, et al. Relation between left ventricular gradients and relative stroke volume ejected in early and late systole in hypertrophic cardiomyopathy: assessment with radionuclide cineangiography. Br Heart J 1984;52:602–9.
30. Bonow RO, Rosing DR, Bacharach SL, et al. Effects of verapamil on left ventricular systolic function and diastolic filling in patients with hypertrophic cardiomyopathy. Circulation 1981;64:787–96.
31. Oakley CM, Raftery EB, Brockington IF, Steiner RE, Goodwin JF. Relation of hypertrophic obstructive cardiomyopathy to subvalvular mitral incompetence (abstr). Br Heart J 1967;29:629.
32. Pridie RB, Oakley CM. Mechanism of mitral regurgitation in hypertrophic obstructive cardiomyopathy. Br Heart J 1970;32:203–8.
33. Jiang L, King ME, Stewart WJ, Levine RA, Weyman AE. Systolic anterior motion of the mitral valve as a predictor of mitral regurgitation in IHSS (abstr). Circulation 1984;70(suppl II):II-17.
34. Rackley CE, Whalen RE, McIntosh HD. Ventricular volume studies in a patient with hypertrophic subaortic stenosis. Circulation 1966;34:579–84.
35. Wigle ED, Marquis Y, Auger P. Pharmacodynamics of mitral insufficiency and muscular subaortic stenosis. Can Med Assoc J 1967;97:299–301.
36. Ross J, Braunwald E, Gault JH, Mason DT, Morrow AG. The mechanism of the intraventricular pressure gradient in idiopathic hypertrophic subaortic stenosis. Circulation 1966;34:558–78.
37. Criley JM, Lewis KB, White RI, Ross RS. Pressure gradients without obstruction: a new concept of "hypertrophic subaortic stenosis." Circulation 1965;32:881–7.
38. Wigle ED, Marquis Y, Auger P. Muscular subaortic stenosis. Initial left ventricular inflow tract pressure in the assessment of intraventricular pressure differences in man. Circulation 1967;35:1100–17.
39. Goodwin JF. Hypertrophic cardiomyopathy: a disease in search of its own identity. Am J Cardiol 1980;45:177–80.
40. Bulkley BH. Idiopathic hypertrophic subaortic stenosis afflicted: idols of the cave and market place. Am J Cardiol 1980;45:177–80.
41. Murgo JP. Does outflow obstruction exist in hypertrophic cardiomyopathy? (editorial). N Engl J Med 1982;307:1008–9.
42. Levine RA, Weyman AE. Dynamic subaortic obstruction in hypertrophic cardiomyopathy: criteria and controversy. J Am Coll Cardiol 1985;6:16–8.