Volume Ejected in Early Systole

A Sensitive Index of Left Ventricular Performance in Coronary Artery Disease

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SUMMARY

Indices based on early systolic ejection rates are theoretically more sensitive to ventricular performance than indices based on the entire systolic ejection (SE) period (mean ejection phase indices-MEPI): mean systolic ejection rate (MSER), mean normalized systolic ejection rate (MNSER) and mean velocity of circumferential fiber shortening (MVcf). The volume ejected in early systole is an indicator of the early rate of ejection. Accordingly, ventricular volume changes were determined by ventriculographic analysis for each third of SE in ml/sec (SER), as normalized systolic ejection rate (NSER), and as percent of stroke volume (PSV). In ten normal controls all these indices were higher in the first third compared to the other thirds of SE. Seven patients with diffuse ventricular disease had depressed values in the first third of SE. Despite "normal" ventriculograms and normal MEPI, eight patients with left anterior descending coronary artery stenoses (> 60%) also had definitely depressed ejection indices during first third of systole. Detailed wall motion analysis in this group showed anteroapical hypokinesis isolated to the first third of SE. These data show that indices based on early SER are more sensitive than MEPI (MVcf, MNSER) for detecting abnormalities in ventricular performance in coronary artery disease.

CORONARY ARTERY DISEASE is a well known cause of regional myocardial dysfunction. Nevertheless, despite the presence of severe coronary stenoses, left ventriculograms are apparently normal in many cases. It has been shown experimentally in dogs that graded, increasingly severe, coronary artery obstructions produce a spectrum of measurable decreases in regional myocardial performance.[1] Such findings suggested that subtle decreases in myocardial function might be more frequently detected on ventriculography in the presence of significant coronary artery stenoses if a sufficiently sensitive test of ventricular performance were available.

Ejection phase indices of left ventricular performance such as ejection fraction (EF), mean velocity of circumferential fiber shortening (MVcf), and mean normalized systolic ejection rate (MNSER) have been demonstrated to be quite useful and generally more reliable than isovolumic phase indices for separating groups of patients.[2, 3] These conventional ejection phase indices, however, measure only the average of all events occurring during systole and do not identify changes occurring in a particular phase of systole. Instantaneous measurements of left ventricular volume change and the velocity of fiber shortening have been determined using quantitative ventriculography[4] and electromagnetic velocity probes[5] but are not considered practical for general application.

In animals the maximum acceleration of blood from the left ventricle at the onset of systolic ejection is recognized as a particularly sensitive indicator of ventricular performance.[6-8] The more rapid the increase in the early systolic ejection rate, the better the ventricular performance and the greater the volume (or fraction of stroke output) ejected during early systole. Previous measurements of left ventricular volume change during systole in man, whether using quantitative left ventriculography[9, 10] or intra-aortic electromagnetic flow probes,[11] have not focused on this early phase of systolic ejection. As a practical approach to detection of variations in the time sequence of ventricular volume change during systole, a method of ventriculographic analysis was devised which divides the period of systolic ejection into three parts. The method permits specific comparisons of systolic output during the first, second, and final thirds of systolic ejection. Particular attention is paid to changes during the first third of systolic ejection.

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Materials and Methods

Patient Groups

Twenty-five patients, 28–62 years of age, were studied during diagnostic left heart catheterization and coronary arteriography. None of the patients had received propranolol during the 24 hours prior to study. Their diagnoses are listed in table 1. The first group (normal group) consisted of ten patients, including seven females and three males aged 42–62 years. All of these patients had diagnostic studies because of chest pain of uncertain etiology. All had heart rates between 57 and 86 (sinus rhythm), and normal aortic and left ventricular end-diastolic pressures (LVEDP) (< 12 mm Hg).

Eight patients (LAD group), including four males and four females, aged 32–55 years were studied because of angina refractory to medical management or angina of recent onset in a young person. All of these patients had single vessel coronary artery disease (CAD) with greater than 60% stenoses of the left anterior descending (LAD) artery. All were considered to have normal left ventriculograms and none had evidence of previous myocardial infarction (MI). All had heart rates from 65–86 beats/min (sinus rhythm), normal aortic pressures and normal LVEDPs.

The third group (myocardial disease group) of seven patients including two females and five males 28–60 years old, had myocardiopathy, in two cases due to atherosclerotic cardiovascular disease (ASCVD) (ischemic) and in the remaining five cases idiopathic. All these patients had symptoms of heart failure and six of the seven had enlarged hearts on conventional chest roentgenograms. All patients in this group were in sinus rhythm; their heart rates ranged from 66–103 beats/min; their brachial or aortic pressures were normal. The LVEDP was elevated at rest in patient JH with ASCVD, became elevated post ventriculogram (40 mm Hg) in patient RM with ASCVD. In the patients with primary myocardial disease (PMD) LVEDPs were normal at rest but became elevated during exercise. The two patients with ASCVD both had widespread CAD with history of multiple MIs but without frank aneurysms or localized dyskinesis (diffusely diminished contractility).

Data Collection

Using a modified Judkins technique coronary arteriography was performed in the postabsorptive state after the administration of seconal, phenergan, and atropine. Following the coronary study a waiting period of 20 minutes was allowed to minimize the effects of the contrast medium on ventricular performance. Left ventriculography was then performed by the retrograde arterial technique using a pigtail catheter. With the patient in the shallow (25°) RAO position and immediately following a moderate inspiration, 45 cc of Renografin-76 were injected over 2–3 sec with a power syringe. Cineangiograms were exposed at 50 frames/sec on 35 mm film. During the cineangiogram, the ECG was recorded on a photographic recorder. The earliest well visualized normal beat in each study was chosen for analysis to minimize the myocardial depressant effects of contrast medium. Cardiac cycles following extrasystoles were not used. All of the patients were in sinus rhythm and none of them showed a significant change in sinus rate during the ventriculogram.

Volume Analysis

Several methods were used to identify important points in the cardiac cycle on the cineventriculograms. In the cine marker system, each cine frame is indicated on the photographic recorder, and with every tenth frame (200 msec) a special mark appears simultaneously on the film and on the ECG recording. The cine frame corresponding with the peak of the R wave on the simultaneously recorded ECG was identified as end-diastole (ED). End-systole (ES) was identified as the smallest visualized ventricular chamber. The frame corresponding to ED was verified by counting frame by frame backwards from ES the number of frames equal to the systolic left ventricular ejection time (LVET), measured from the aortic pressure tracing plus the preejection period (PEP), assumed to be equal to 50 msec in the normal and LAD groups. The PEP in the group with myocardial disease was considered equal to the interval from the peak of the R wave on the ECG to the beginning of the upstroke of the aortic pulse minus the delay time for pressure transmission in a fluid-filled catheter system measured in our laboratory to be 0.02 sec. Opening and closing of the aortic valve when visualized were also used to identify the beginning of left ventricular ejection and ES. The last frame in which the aortic valve was visualized in the closed position was assumed to be the end of the PEP and the last frame in which the aortic valve was visualized in the open position was assumed to be ES. In each case the LVETs derived from the angiocardiogram and from the aortic pressure tracing were equivalent.

The silhouette of the left ventricular cavity was traced in outline at ED, at ES, at the end of the PEP, and the end of the first and second thirds of systole (fig. 1). The LVET was divided into three equal parts. If the LVET was not evenly divisible by three, then the first and second thirds were made equal in duration and the last third either one frame longer or one frame shorter than the first two thirds. The tracings were always made to the outside margins of the papillary muscles. The long axis of the left ventricle was taken as the longest measured line from the apex to the margin of the aortic valve.

Ventricular volumes were measured using the single plane area-length method of Dodge.[12] A calibrated metal grid filmed in a position corresponding to the LV during the study was utilized for obtaining correction factors for magnification. In this laboratory regression equations are not used to correct for presumed error in roentgenographic ventricular volume determinations for reasons previously reported.[13]

The volume at the end of the first third was subtracted from the volume at the end of the PEP.[14] The volume at the end of the second third of systole was subtracted from the volume at the end of the first third. End-systolic volume was subtracted from the volume at the end of the second third of systole. Each volume change in ml was divided by the time period over which it occurred and the ejection rate expressed as ml/sec. Volume changes were also expressed as a percent of stroke volume.

Each ejection rate was normalized by dividing by the volume at the beginning of that particular ejection period, giving a normalized systolic ejection rate (NSER). In addition, the ejection rate for all of systolic ejection was calculated as:

$$\text{MNSER} = \frac{\text{SV}}{\text{LVET} \times \text{EDV}}$$

It has been indicated that such normalized ejection rates permit meaningful comparisons among patients.[15]

Table 1

Standard Hemodynamic, Angiographic Data and Diagnoses in Normal Patients, Patients with LAD Obstructions and Patients with Diffuse Myocardial Disease

Pt	Sex	Age	SP/DP (mm Hg)	HR (beats/min)	LVEDP (mm Hg)	LVEDVI (ml/m²)	SI (ml/m²)
Normals							
C.S.	M	42	120/80	86	8	79	48
M.S.	F	51	135/70	86	10	65	47
L.F.	F	54	110/62	62	8	72	47
J.C.	F	53	140/80	85	10	64	47
S.K.	F	53	120/80	75	8	63	36
M.O.	F	62	120/90	86	9	70	49
L.A.	M	47	120/70	57	10	82	55
P.R.	F	52	105/60	92	2	84	53
L.H.	F	58	115/65	75	5	75	54
M.M.	M	47	105/60	63	5	73	46
Mean ± SD		52 ± 6	119 ± 12 / 72 ± 10	77 ± 12	8 ± 3	73 ± 7	48 ± 5
Single Vessel LAD							
S.G.	M	48	140/70	86	11	93	52
J.M.	M	52	140/90	80	12	64	38
A.R.	M	32	110/70	85	6	68	46
M.W.	F	40	130/70	66	5	97	59
A.A.	M	46	110/60	65	10	59	40
I.T.	F	50	140/80	67	10	82	56
A.S.	F	55	130/80	73	5	56	38
M.Y.	F	41	95/60	75	12	92	60
Mean ± SD		46 ± 8	124 ± 17 / 73 ± 10	75 ± 8	9 ± 3	76 ± 17	49 ± 9
P value		NS	NS	NS	NS	NS	NS
Myocardial Disease							
S.A.	F	60	135/80	86	12	95	38
R.M.	M	45	120/80	66	10	98	44
J.H.	M	45	90/60	100	15	178	43
W.K.	M	41	118/80	103	8	103	42
Ma.J.	F	45	105/80	80	10	187	42
J.G.	M	28	125/80	86	10	259	44
Me.J.	M	39	110/80	100	5	125	57
Mean ± SD		43 ± 10	115 ± 15 / 77 ± 8	89 ± 13	10 ± 3	140 ± 61	44 ± 6
P value		.05	NS	NS	NS	.01	NS

Abbreviations: LAD = left anterior descending; Pt = patient; SP = systolic pressure; DP = diastolic pressure; HR = heart rate; LVEDP = left ventricular end-diastolic pressure; LVEDVI = left ventricular end-diastolic volume index; SI = stroke index; EF = ejection fraction; S_1 = first septal branch; D_1 = first diagonal branch; RCA = right coronary artery; PMD = primary myocardial disease; ASCVD = atherosclerotic cardiovascular disease; DAM = diffuse abnormal wall motion; NS = not significant; SD = standard deviation.

Wall Motion Analysis

Using these same tracings of the outline of the left ventricular silhouette at ED, end of the PEP, and end of the first and second thirds of systolic ejection, and at ES, measurements of regional wall motion were made. On each tracing a long axis was constructed from the apex to the middle of the aortic valve. Three equally spaced perpendicular chords (segmental diameters) to the long axis of each tracing were constructed. The shortening of each of these three chords and of the anterior and inferior segments of each chord (six hemiaxes) were measured for each third of systole (fig. 2).[16] The resulting changes in lengths were expressed as percentages of the chord (or hemiaxis) lengths at the beginning of the third being analyzed.

Using the diaphragm and the position of the image intensifier as fixed reference points, none of the films showed evidence of patient movement (breathing) or camera motion during the ventriculogram. For visual comparison as shown in figure 2 the long axes of the sequential ventricular outlines were rotated about their aortic valve origins until parallel with the long axis at ED and then superimposed on it.[17] In the case of dilated ventricles with myocardial disease, the apical point was arbitrarily selected in the center of the rounded apical region. In some normal cases with high ejection fractions, the apex appeared to become obliterated by the papillary muscles and trabeculations during the final third of systole. In these cases the apex, which was well visualized at the end of the second third of systole, was used as the apical point for the end-systolic drawing.

Mean Vcf was calculated using the internal diameters in the equatorial plane measured directly from the tracings of the end-diastolic and end-systolic outlines.[18] The normalized velocity of circumferential fiber shortening (Vcf) for each third of systole was also calculated using directly measured diameters. The equatorial diameter at the end of each third was subtracted from the diameter at the beginning of the

EF (%)	Ventriculogram	Coronary arteriogram (% obstruction)	Diagnosis
61	Normal	Normal	Atypical chest pain
70	Normal	Normal	Atypical chest pain
65	Normal	Normal	Atypical chest pain
73	Normal	Normal	Atypical chest pain
58	Normal	Normal	Atypical chest pain
70	Normal	Normal	Atypical chest pain
67	Normal	Normal	Atypical chest pain
64	Normal	Normal	Atypical chest pain
72	Normal	Normal	Atypical chest pain
63	Normal	Normal	Atypical chest pain
66 ± 5			
57	Normal	85% proximal LAD	ASCVD
60	Normal	70% proximal LAD distal to S_1	ASCVD
67	Normal	99% proximal LAD, distal D_1, 50% of D_1	ASCVD
62	Normal	85% proximal LAD	ASCVD
68	Normal	90% proximal LAD	ASCVD
69	Normal	80% proximal LAD, 50% of D_1	ASCVD
69	Normal	60% proximal LAD, 85% of D_1	ASCVD
65	Normal	60% proximal LAD	ASCVD
65 ± 5			
NS			
40	DAM	Normal	PMD
45	DAM	Occluded RCA, 90%, proximal LAD	ASCVD
24	DAM	Occluded RCA, circumflex, 80% proximal LAD	ASCVD
40	DAM	Normal	PMD
22	DAM	Normal	PMD
17	DAM	Normal	PMD
46	DAM	Normal	PMD
33 ± 12			
.001			

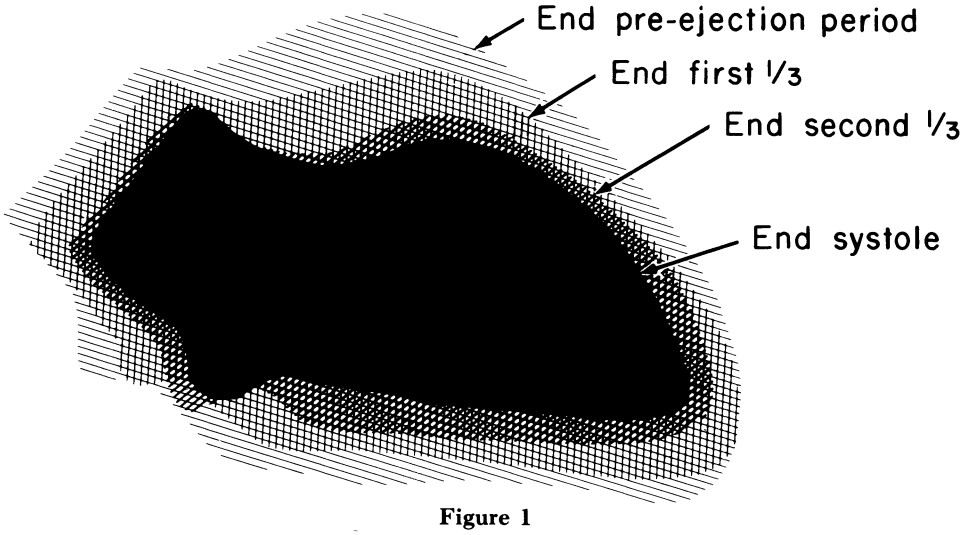

Figure 1

Left ventricular silhouettes traced at the end of the pre-ejection period (outer margin of lightly shaded area), end of the first third of systolic ejection (outer margin of more darkly shaded area), and end of the second third of systolic ejection (outer margin of darkest shaded area), and at end-systole (outer margin of black area).

third. This result was then divided by the time interval over which the measured diameter change occurred (usually about 100 msec) and normalized by the diameter at the beginning of each third.

Results

The standard hemodynamic and angiographic data for all three groups are recorded in table 1 and mean ejection phase indices as well as ejection indices for thirds of systole in table 2.

Standard Ejection Phase Indices

There were no significant differences in the standard ejection phase indices between the ten patients without ventricular disease and the eight patients with single vessel LAD disease. Ejection fraction (EF) averaged 66 ± 5 (mean ± SD) (range 61–73) and 65 ± 5 (range 57–69), respectively. Mean velocity of circumferential fiber shortening (MVcf) values expressed as end-diastolic circumferences/sec averaged 1.30 ± 0.15 (range 1.07–1.63) in the normal group and 1.32 ± 0.20 (range 1.09–1.63) in the group with LAD disease. Mean normalized systolic ejection rate (MNSER) averaged 2.29 ± 0.17 in the normal group (range 2.07–2.65) and 2.17 ± 0.20 in the LAD group (range 1.88–2.47). In contrast, in the myocardial disease group the values for each of these indices were significantly lower than normal. EF averaged 33 ± 12 (range 17–46) ($P < .001$); MVcf averaged 0.60 ± 0.24 (range 0.19–1.00) ($P < .001$) and MNSER averaged 1.27 ± 0.40 (range 0.66–1.92) ($P < .001$).

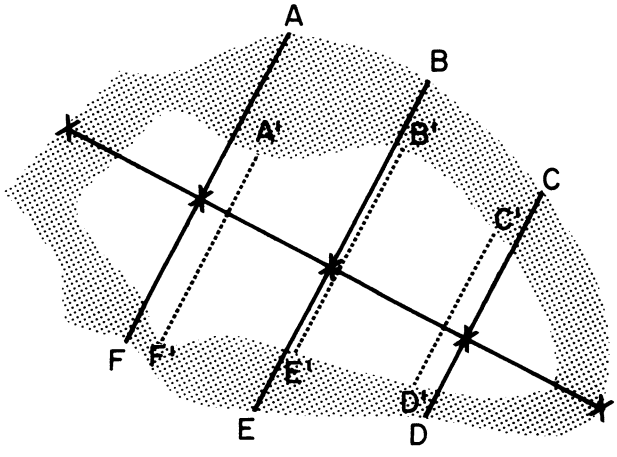

Figure 2

Left ventricular silhouettes traced at the end of the pre-ejection period (outer margin of shaded area) and end-systole (outer margin of white area). On each silhouette a long axis is constructed from the center of the aortic valve to the apex. Three equally spaced perpendiculars to this long axis are constructed. The solid perpendicular lines represent the basal, equatorial, and apical chords at the onset of systolic ejection (AF, BE, CD, respectively). The dotted lines represent the three chords at end-systole (A'F', B'E', C'D', respectively). For the analysis of the sequence of ventricular contraction, tracings are made at the end of the first and second thirds of systolic ejection.

Rates of Volume Change for Thirds of Systole

The mean rate of volume change for the first third of systole expressed as ml/sec was significantly lower in the LAD group than in the normal group, averaging 238 ± 49 (range 168–280) and 374 ± 56 (range 260–450) respectively, ($P < 0.001$) (fig. 3.) In contrast, during the second third of systole the mean rate of volume change was significantly higher in the LAD group than in the normal group, averaging 374 ± 82 (range 208–462) and 283 ± 50 (range 190–362), respectively ($P < 0.01$).

Although there was some overlap between the two groups during both the first and second thirds of systolic ejection, each of the patients in the normal group ejected more blood during the first third than during the second third of systole and each of the patients in the LAD group ejected more blood during the second third than during the first third.

In the myocardial disease group mean rate of volume change during the first third averaged 203 ± 84 (range 120–375), significantly lower than in the normal group ($P < 0.01$). During the second third mean rate of volume change averaged 384 ± 109 (range 270–562), significantly higher than in the normal group ($P < 0.01$). The patterns of volume change in the myocardial disease group and LAD group were similar (fig. 3).

For the final third of systole the mean rate of volume change averaged 210 ± 73 (range 125–340) in

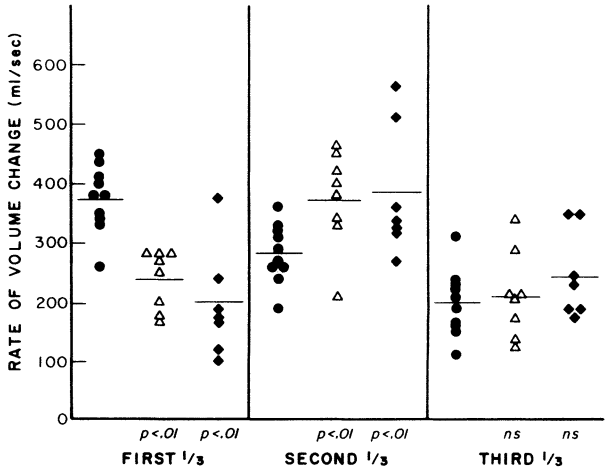

Figure 3

The rate of volume change in milliliters per second for thirds of systolic ejection is plotted on the vertical axis for patients with normal left ventricular function (black circles), patients with left anterior descending coronary stenoses (white triangles), and patients with myocardial disease (black diamonds). Overlap between the normal and LAD groups for the first third is apparent. Horizontal bars indicate the mean value for each group.

Table 2

Mean Ejection Phase Indices and Ejection Indices for Thirds of Systole

Pt	MVcf	MNSER	Rate of volume change for thirds (ml/sec)			Volume change for thirds as % SV			NSER for thirds			Vcf for thirds		
			1	2	3	1	2	3	1	2	3	1	2	3
Normals														
C.S.	1.29	2.15	400	330	312	40	33	25	2.41	2.66	3.43	1.20	1.70	1.75
M.S.	1.16	2.26	330	240	110	47	34	19	3.40	3.80	2.97	1.60	1.60	2.42
L.F.	1.29	2.30	380	290	230	45	34	21	2.88	3.09	3.54	1.00	1.40	2.00
J.C.	1.33	2.41	380	270	240	45	32	23	3.28	3.51	4.74	1.70	1.40	2.50
S.K.	1.07	2.07	260	190	162	44	32	22	2.55	2.57	2.95	1.00	1.10	1.50
M.O.	1.33	2.34	350	310	160	43	38	20	2.99	3.73	3.14	1.10	1.60	1.70
L.A.	1.30	2.23	450	320	190	45	32	19	3.04	3.20	2.79	1.20	1.90	1.20
P.R.	1.63	2.65	438	362	225	40	33	21	3.20	3.73	3.31	1.75	1.75	2.00
L.H.	1.37	2.39	410	260	150	48	30	17	3.42	3.47	3.06	1.30	1.70	1.60
M.M.	1.23	2.11	340	260	210	40	31	25	2.56	2.71	3.00	1.00	1.40	1.70
Mean ± SD	1.30	2.29	374	283	199	44	33	21	2.97	3.25	3.29	1.28	1.56	1.84
	±0.15	±0.17	±56	±50	±57	±3	±2	±3	±0.37	±0.47	±0.56	±0.29	±0.23	±0.40
Single Vessel LAD														
S.B.	1.40	1.88	200	450	340	19	43	32	1.08	2.81	2.96	0.80	1.30	2.60
J.M.	1.63	2.47	175	462	287	18	49	30	1.37	4.13	3.83	0.88	2.00	2.88
A.R.	1.46	2.40	280	380	212	33	44	20	2.19	3.92	3.59	1.20	2.40	1.75
M.W.	1.13	2.05	270	400	170	31	45	19	1.89	3.57	2.36	0.80	1.60	1.30
A.A.	1.47	2.13	250	340	125	32	43	19	2.16	3.95	2.40	1.40	1.90	1.83
I.T.	1.27	2.28	280	330	210	34	40	26	2.33	3.63	3.62	0.80	1.70	1.90
A.S.	1.14	2.14	168	208	133	31	38	25	1.77	2.97	2.96	0.70	1.20	1.75
M.Y.	1.09	2.01	280	420	208	29	43	26	1.85	3.47	2.67	0.90	1.30	1.25
Mean ± SD	1.32	2.17	238	374	210	28	43	25	1.83	3.56	3.05	0.93	1.68	1.91
	±0.20	±0.20	±49	±82	±73	±6	±3	±5	±0.43	±0.47	±0.57	±0.24	±0.41	±0.57
P value	NS	NS	.01	.01	NS	.001	.001	NS	.001	NS	NS	.02	NS	NS
Myocardial Disease														
S.A.	0.63	1.34	120	270	190	18	42	29	0.74	1.89	1.64	0.20	0.90	0.70
R.M.	0.73	1.49	240	360	230	28	42	27	1.25	2.18	1.78	0.80	0.80	0.63
J.H.	0.50	1.11	175	562	350	16	50	23	0.48	1.63	1.17	0.25	0.75	0.17
W.K.	0.57	1.35	170	320	220	22	41	28	0.88	1.89	1.61	0.20	0.80	0.60
Ma.J.	0.55	1.02	150	325	350	18	39	31	0.50	1.16	1.38	0.17	1.17	0.50
J.G.	0.19	0.66	188	338	190	20	36	26	0.44	0.84	0.51	0.38	0.25	0.10
Me.J.	1.00	1.92	375	512	175	33	45	15	1.88	3.14	1.43	1.25	1.50	0.75
Mean ± SD	0.60	1.27	203	384	244	22	42	26	0.88	1.82	1.36	0.46	0.88	0.49
	±0.24	±0.40	±84	±109	±75	±6	±5	±5	±0.53	±0.74	±0.42	±0.41	±0.39	±0.26
P value	.001	.001	.01	.01	NS	.001	.001	.05	.001	.001	.001	.001	.001	.001

Abbreviations: LAD = left anterior descending; Pt = patient; MVcf = mean velocity of circumferential fiber shortening; MNSER = mean normalized systolic ejection rate; SV = stroke volume; NSER = normalized systolic ejection rate; Vcf = velocity circumferential fiber shortening normalized for initial circumference; NS = not significant; SD = standard deviation.

the LAD group, 244 ± 75 (range 175–350) in the myocardial disease group, and 199 ± 57 (range 110–312) in the normal group. There were no significant differences among these values.

Volume Change for Thirds of Systole as Percentage of Stroke Volume

The results of volume change for the thirds of systole expressed as percentage SV for the three groups are similar to the results of rates of volume change (fig. 4). Volume change as percentage SV for the first third of systole in the LAD group was significantly lower than in the normal group, averaging 28 ± 6 (range 18–34) and 44 ± 3 (range 40–48), respectively ($P < 0.001$), and during the second third it was higher in the LAD group than in the normal group, averaging 43 ± 3 (range 38–49) and 33 ± 2 (range 30–38), respectively ($P < 0.001$). During the final third of systole there was no significant difference in volume change as percentage SV between the two groups, averaging 25 ± 5 (range 19–32) in the LAD group and 21 ± 3 (range 17–25) in the normal group. This index, when compared to mean rate of volume change, better separates the normal and LAD groups because it takes into account normal variance in ventricular size.

The pattern of left ventricular ejection in the myocardial disease group was again similar to the LAD group. Volume change as percentage SV for the first third of systole was significantly lower than normal, averaging 22 ± 6 (range 16–33) ($P < 0.001$), and for the second third of systole significantly higher than normal, averaging 42 ± 5 (range 36–50) ($P < 0.001$). For the final third of systole volume change as percentage SV was slightly higher in the group with myocardial disease than in the normals, averaging 26 ± 5 (range 15–31) ($P < 0.05$).

Normalized Systolic Ejection Rates for Thirds of Systolic Ejection

Similar to mean rate of volume change and volume change as percentage SV, NSER for the first third of systole was lower in the LAD group than in the normal group, averaging 1.83 ± 0.43 (range 1.08–2.33), and 2.97 ± 0.37 (range 2.41–3.42), respectively ($P < 0.001$). There was no overlap of values for NSER for the first third of systole between these two groups (fig. 5). In contrast to mean rate of volume change and volume change as percentage SV, NSER for the second third of systole was not significantly different in the LAD group than in the normal group, averaging 3.56 ± 0.47 (range 2.81–4.13) and 3.25 ± 0.47 (range 2.57–3.80), respectively. This difference is the consequence of normalization of the LAD group's higher rate of volume change in the second third by a larger volume at the beginning of the second third, in turn a result of reduced ejection during the first third by the LAD group.

In the group with myocardial disease, because of abnormally large volumes throughout systole, NSERs for all three thirds were significantly ($P < 0.001$) lower than in the other two groups, averaging 0.88 ± 0.53 (range 0.44–1.88) for the first third, 1.82 ± 0.74 (range 0.84–3.14) for the second third, and 1.36 ± 0.42 (range 0.51–1.78) for the third third.

Change in Segmental Chords and Hemiaxes for Thirds of Systole

There were no significant differences between the

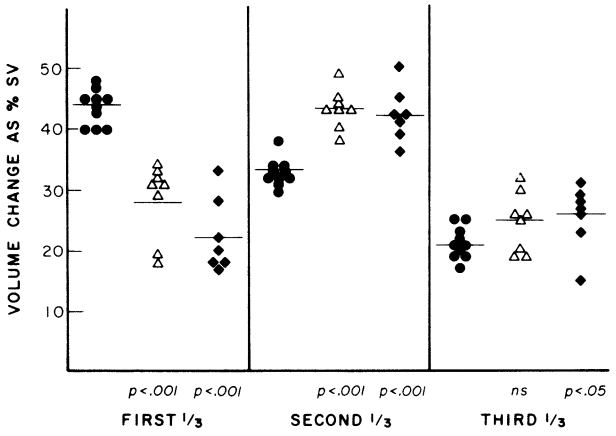

Figure 4

Volume change for thirds of systolic ejection as percentage stroke volume is plotted on the vertical axis for the normal (black circles), LAD (white triangles), and myocardial disease (black diamonds) groups. There is no overlap between the normal and LAD groups for the first third of systole. Horizontal bars indicate the mean values for each group.

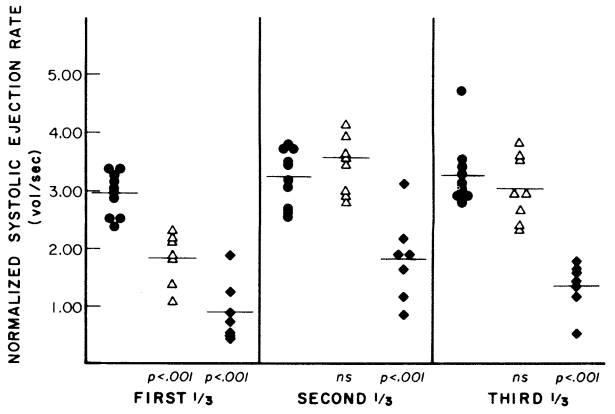

Figure 5

Normalized systolic ejection rate in volumes/sec (NSER) for thirds of systolic ejection is plotted on the vertical axis for the normal (black circles), LAD (white triangles), and myocardial disease (black diamonds) groups. There is no overlap between the normal and LAD groups for the first third of systole. Horizontal bars indicate the mean values for each group.

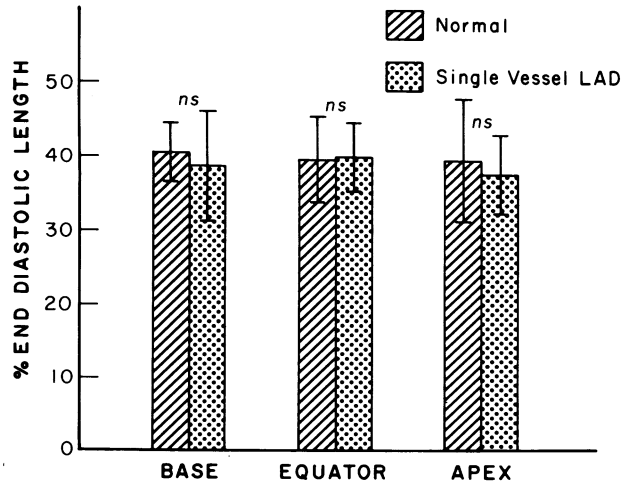

Figure 6

Total systolic shortening of the basal, equatorial, and apical chords as percentage of end-diastolic length for the normal (striped bars) and LAD (stippled bars) groups is plotted on the vertical axis. Each bar represents the mean ± one standard deviation. No significant differences were found.

normal and LAD groups in total systolic shortening of the three segmental chords expressed as percentage end-diastolic length. Shortening of the basal chord averaged 41 ± 4 (range 36–49) in the normals, 39 ± 7 (range 28–47) in the LAD group; shortening of the equatorial chord averaged 40 ± 6 (range 30–50) and 40 ± 5 (range 35–48); and shortening of the apical chord 40 ± 8 (range 28–55) and 37 ± 5 (range 29–43) in the two groups respectively (fig. 6).

For the first third of systole, however, the LAD group showed significantly lower percentages shortening of the equatorial and apical chords when compared to the normals, the values for these two chords averaging 9 ± 3 (range 7–14) and 9 ± 3 (range 2–12) in the LAD group and 13 ± 3 (range 10–17) and 14 ± 5 (range 4–22) in the normal group, ($P < 0.05$). For the second and third thirds of systole there were no significant differences between these two groups (fig. 7).

The differences in chord shortening during the first third of systole between these two groups appears to be due entirely to differences in shortening of the anterior hemiaxes (fig. 7). The anterior equatorial and anterior apical hemiaxes in the LAD group shortened 6 ± 4 (range 2–11) and 3 ± 4 (range −2–10), respectively, and in the normal group 12 ± 5 (range 6–23) and 13 ± 7 (range 4–28), respectively ($P < 0.05$). In contrast, there were no significant differences in percentages shortening of the inferior equatorial and inferior apical hemiaxes for the first third between these two groups, values averaging 12 ± 6 (range 5–26) and 15 ± 5 (range 3–21) in the LAD group and 12 ± 6 (range 7–27) and 14 ± 7 (range 2–20) in the normal group. Because the basilar hemiaxes

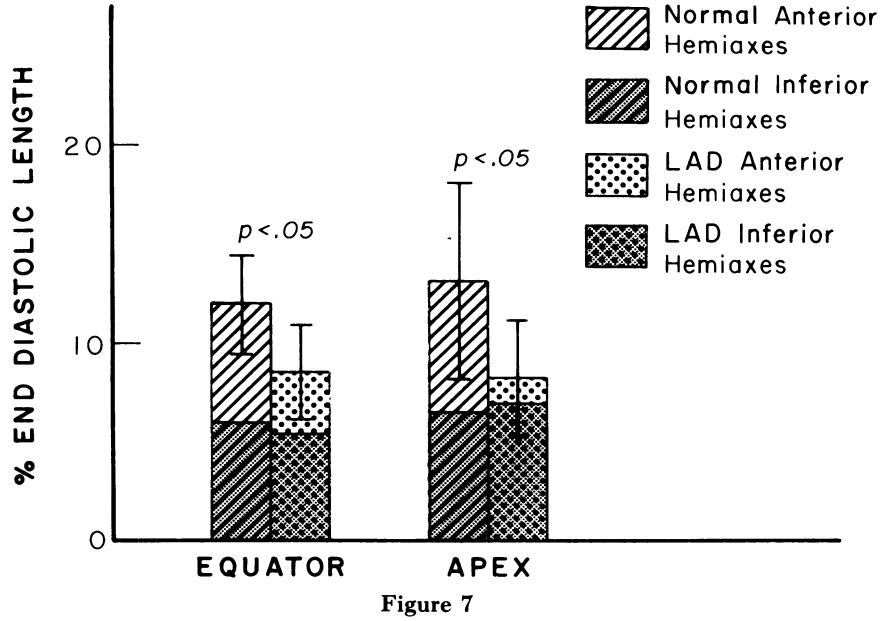

Figure 7

Percent shortening of the apical and equatorial chords for the first third of systolic ejection for the normal (striped bars) and LAD (stippled bars) groups is plotted on the vertical axis. The top of each bar represents the mean shortening of the chords ± one standard deviation. A horizontal line dividing each bar separates the component contributed by the anterior hemiaxes (top parts) from the component contributed by the inferior hemiaxes (bottom parts). The significantly slower rate of shortening during the first third in the LAD group (P < 0.05) is shown to be the consequence of delayed motion of the anterior hemiaxes representing the region supplied by the stenotic LAD.

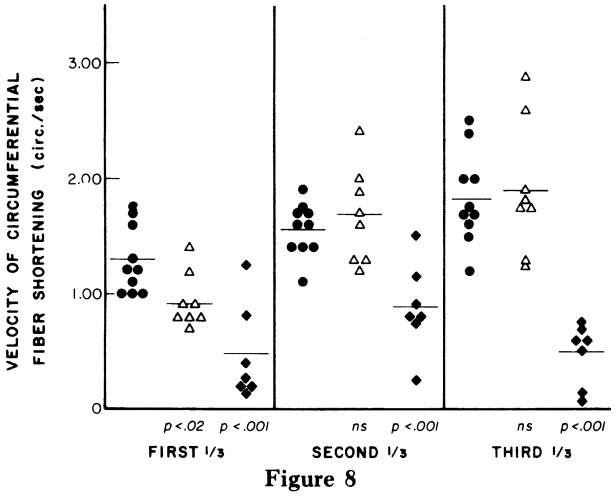

Figure 8

Velocity of circumferential fiber shortening for thirds of systolic ejection in circumferences per second (Vcf) is plotted on the vertical axis for the normal (black circles), LAD (white triangles), and myocardial disease (black diamonds) groups. There is considerable overlap between the normal and LAD groups for the first third. Note: the one patient in the myocardial disease group with a value for Vcf for the first third in the normal range was a patient (MeJ) with alcoholic myocardiopathy who, when studied after a favorable treatment with bedrest, had only minimally impaired left ventricular performance.

(including the mitral valve) showed a wide variation in percentages of shortening the data for these hemiaxes are not presented in detail.

In the group with myocardial disease the percentages of shortening of the three chords and six hemiaxes were much less than normal. All patients in this group had diffusely diminished LV wall motion without discrete areas of dyssynergy.

Velocity of Circumferential Fiber Shortening for Thirds of Systole

Similar to the other ejection indices for the first third of systole, Vcf was significantly lower for the first third in the LAD group than in the normal group, averaging 0.93 ± 0.24 (range 0.70–1.40) and 1.28 ± 0.29 (range 1.00–1.75), respectively ($P < 0.02$). Vcf did not, however, separate these two groups as well as the other indices (fig. 8). For the second and third parts of systole there were no significant differences in average Vcf values between the two groups. For the second third Vcf averaged 1.56 ± 0.23 (range 1.10–1.90) in the normals, 1.68 ± 0.41 (range 1.20–2.40) in the LAD group, and for the third part of systole Vcf averaged 1.84 ± 0.40 (range 1.20–2.50) in the normals and 1.91 ± 0.57 (range 1.25–2.88) in the LAD group.

Within the normal group Vcf was lower for the first third than for the second and third parts of systole (table 2). A particular fiber shortening rate results in ejection of a greater volume of blood in a large ventricle (e.g. early systole) than in a smaller ventricle (late systole) and therefore a greater volume change occurs in the first third in the normal group even though Vcf is greater in the second third.

Discussion

Ventricular performance is dependent not only upon the inotropic state of the myocardial contractile fibers but also on preload, afterload, ventricular geometry, and mass and distribution of the myocardium, the synchrony of muscle excitation and the character and distribution of noncontractile components of the ventricular wall.[19] It would be very helpful to have a means of measuring the contractile state of the human heart, separate from the effects of preload, afterload, and other modifying factors. It is emphasized, however, by use of the term performance instead of contractility that there is at present no generally accepted index of contractility of the human heart which is totally independent of modifying factors. Available indices of left ventricular performance can mainly be divided into two groups depending upon whether the primary data are obtained during the isovolumic (pre-ejection) phase or during the ejection phase of ventricular systole. Recent studies have indicated that the ejection phase indices such as EF, MVcf, MNSER are preferable for separating abnormal from normal ventricles in the basal state.[3, 19]

All of these ejection phase indices (EF, MNSER, MVcf) reflect left ventricular end-diastolic size since all are normalized by this quantity. MVcf is regarded as a more useful index than EF in presence of valvular insufficiency.[20, 21] In the presence of wall motion disorders, on the other hand, mean normalized systolic ejection rate (MNSER), which is calculated on the basis of changes in the entire ventricular outline, is considered more sensitive than MVcf.[3] When ventricular performance is severely impaired, however, EF may be the better index. This is because MNSER is equivalent to EF divided by left ventricular ejection time (LVET) and LVET shortens as ventricular performance becomes severely impaired.

Volume Change in Early Systole

None of the conventional ejection phase indices (EF, MVcf, MNSER) discussed above focuses in detail upon the events of systole but rather expresses the mean or average of values occurring during systole. Ventricular ejection rate, however, is not constant but changes rapidly especially at the beginning of ejection.[7] The onset of systole is characterized by rapid force development[6, 22] and a correspondingly rapid increase in ejection rate.[6, 7] Indeed, blood flow out of the ventricle later in systole is maintained in part by the energy of momentum given to the aortic blood during the earlier phase of ejection.[23] In a particular ventricle

the initial force active from the beginning of ejection to the attainment of near peak ejection velocity is more characteristic of ventricular performance than is the total volume ejected or power produced.[22, 24, 25] The initial ventricular impulse is an appropriate descriptive term for these dynamic properties of ventricular ejection.[22]

This initial ventricular impulse or ejectile force determines the rate of increase of blood flow (ejection) from the ventricle into the aorta. The volume of blood ejected in early systole is a consequence of, and therefore a potential measure of, the initial ventricular impulse (i.e., of ventricular performance). The greater the relative or absolute volume change in the first third of systolic ejection the better is the ventricular performance. Our data are consistent with this concept.

For example, all of the normal patients ejected more blood during the first third than during the second third of the systolic ejection period, while all of the group with isolated LAD stenoses and also all of the myocardial disease group ejected less blood during the first third than during the second third. The similar patterns of systolic volume change in the LAD and myocardial disease groups imply that a slow rate of volume change (or mean fiber shortening) in early systolic ejection relative to mid systolic ejection is characteristic of depressed ventricular performance whether this is subtle (LAD group) or marked (myocardial disease group).

Comparison of ejection rates between different sized ventricles may be facilitated by normalizing to (dividing by) end-diastolic volume.[15] End-diastolic volumes in both the normal and the LAD groups were within the range of normal. When, however, these volumes were used to normalize the rates of volume change (ml/sec) during the first third of systole, improved separation of the LAD group from the normal group was possible (fig. 5). Better separation of these two groups also resulted when the volume changes were expressed as a percent of stroke volume. Since the myocardial disease group characteristically had abnormally large end-diastolic volumes, normalization of ejection rates by EDV further separated this group from the normal.

Regional Dyssynergy During Early Ejection

The subtle depression in ventricular performance exhibited by our patients with greater than 60% LAD stenoses could be the consequence of a previous, clinically silent subendocardial myocardial infarction. Much more likely, however, it is the consequence of reduced myocardial contractility, an adaptation of the myocardium to the reduced blood supply available via the stenotic LAD.[1, 26] Theoretically, such a decrease in contractility matches regional myocardial oxygen consumption to oxygen available from regional blood flow.[27]

The latter interpretation is supported by our regional wall motion studies of the LAD group compared to the normal group. The hemiaxes which recorded motion of the anterior apical wall of the left ventricle (the region corresponding to the distribution of the obstructed LAD) shortened significantly less than normal during the first third of systole, even though no over-all abnormality in total systolic shortening of the segmental chords was detected. Regional hypokinesis seen exclusively in early systolic ejection in the distribution of significantly stenotic coronary arteries (tardokinesis) has been reported previously.[28] This subtle form of dyssynergy in our patients with LAD obstructions appears to explain the slow initial rate of volume change for the first third. This dyssynergy during early systolic ejection also explains the differences in sensitivity between the indices NSER and Vcf for the first third of systolic ejection in the LAD group. Vcf is calculated only on the basis of changes in the ventricular equatorial (midplane) diameter alone, while NSER is based on changes of outline of the entire ventricle including the most severely affected anteroapical region.

Myocardial revascularization may improve regional wall motion in the distribution of the grafted vessel.[29-32] One of our patients with isolated LAD disease was studied before and after saphenous vein bypass. Definite improvement in the rate of early systolic ejection followed the operation. Further studies before and after revascularization are needed.

Evaluation of Method

The method of analysis presented here is highly dependent upon accurate identification of certain important points in the cardiac cycle. An error of 20–40 milliseconds (one or two cine frames at rate of 50 frames/sec) could shift the maximal rate of volume change from the first to second third of systole or vice versa. In each case several methods were used separately to identify each frame used. For example, the cine marker system was used and the frames representing end-diastole, end-preejection period and end-systole were selected. Then, for the same beat, opening and closing of the aortic valve was used to select frames. Finally for the same beat end-systole was found visually and end-diastole found by counting frame by frame backwards from end-systole the number of frames equal to LVET plus PEP. Each ventriculogram analyzed had to be of good enough quality so that at least two, and preferably three, of these methods to identify frames could be used. In each case at least two methods when used separately on the same beat had to identify identical frames

before the data from this ventriculogram were included in this study.

The ventriculograms were performed at least 20 minutes after the coronary studies in all patients in this study. It has been shown that prior coronary artery contrast injection does not affect LV performance in normals but may depress performance in patients with severe CAD and dyssynergy.[33] Our LAD group had single vessel CAD without gross dyssynergy. However, even if the subtle depressions in LV performance found in our LAD group were induced by the prior coronary artery contrast injections, this does not change the significance of our data. The method is sensitive enough to detect a subtle form of dyssynergy, even if the dyssynergy could possibly have been induced by prior contrast material injection.

Single plane rather than biplane ventriculography was utilized in this study. It has been shown that in the presence of CAD, biplane filming is an advantage in quantitating dyssynergy.[34] In our study, however, single plane RAO projection displays well the major portion of the anterior wall supplied by the LAD. Studying patients with other lesions, such as those in the circumflex, would require the LAO projection.

The number of patients in the LAD group is small. Isolated significant obstructions of the LAD without infarction, however, are not very common lesions in our experience, an observation which is supported by other studies which emphasize the diffuse nature of coronary disease.[35, 36] Clearly there must be a group of patients with less significant or mild isolated obstructions of the LAD who will exhibit no functional abnormality. Such patients, however, probably have a low or nil incidence of anginal pain and, therefore, would seldom be subjected to coronary arteriography. The finding of a subtle depression in ventricular performance in the presence of a coronary artery stenosis of otherwise uncertain significance may prove helpful in patient evaluation. This method of ventriculographic analysis of the thirds of systole also has potential usefulness in the assessment of the effects of coronary artery bypass surgery on myocardial function.

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Volume ejected in early systole. A sensitive index of left ventricular performance in coronary artery disease.

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