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DIAGNOSTIC TECHNIQUES

Epicardial Wall Motion and Left Ventricular Function During Coronary Graft Angioplasty in Humans

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Epicardial wall motion and left ventricular function changes during temporary coronary artery occlusion were assessed in a patient at the time of percutaneous transluminal angioplasty performed on a previously placed stenotic coronary artery bypass graft. Epicardial wall motion was analyzed using biplane cineradiography with frame to frame measurements of distances between pairs of radiopaque epicardial markers placed at the time of previous cardiac surgery. Bypass graft occlusion after initial dilation led to the early onset of a biphasic epicardial late systolic lengthening and early diastolic shortening similar to the regional wall motion abnormality preceding the procedure.

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Numerous reports (1–4) exist describing the acute changes in hemodynamics and left ventricular function after coronary occlusion in animals. Much less, however, is known of such changes in humans. Extrapolating results from animals to humans is potentially difficult because in humans preexisting atherosclerotic coronary disease, regional left ventricular dysfunction and a unique distribution of collateral circulation (5) may influence findings.

Our laboratory previously reported (6,7) the dynamic endocardial wall motion and myocardial wall thickness changes accompanying acute coronary occlusion in patients undergoing percutaneous transluminal coronary angioplasty. In these studies, the motion of the region of ischemic myocardium was characterized by the early appearance of a late systolic outward expansion followed by an early diastolic inward contraction. We refer to this biphasic motion as the W phenomenon because of its morphologic characteristics, transient duration and frequent appearance in studies of endocardial and wall thickness motion during regional ischemia. Similar types of wall motion abnormalities have been described with acute ischemia in animals (1,2,4) and with chronic ischemia in humans (8,9). Because phasic wall motion can generally be encountered whenever spatial or temporal nonuniformities in regional contraction or relaxation in the left ventricle exist, the specific cause of this pattern during acute ischemia is uncertain.

Recently, we had the opportunity to extend these observations by evaluating the epicardial length-pressure changes accompanying acute coronary occlusion in a patient undergoing angioplasty of a coronary artery bypass graft in whom pairs of epicardial wall markers had been placed at the time of his original cardiac surgery.

Case Report

The patient is a 47 year old man who presented with severe symptoms of exertional chest pain in 1975. Angiographic evaluation disclosed significant stenoses of the left main, left anterior descending and right coronary arteries, and he underwent coronary bypass surgery with a graft placed in the left anterior descending, obtuse marginal and posterior descending vessels. At the time of surgery, the patient was entered into a prospective study evaluating the use of epicardial wall markers for long-term assessment of graft patency and left ventricular function as previously described (10). Recurrent symptoms in January 1984 led to angiography, which revealed the presence of a severe distal stenosis of the left anterior descending bypass graft, occlusion of the obtuse marginal bypass graft and a high grade stenosis of the distal circumflex artery, in addition to the lesions previously identified (Fig. 1). The right coronary artery was filled by a patent bypass graft and provided collateral flow to the left anterior descending artery. Right anterior oblique left ventricular angiography showed a mildly

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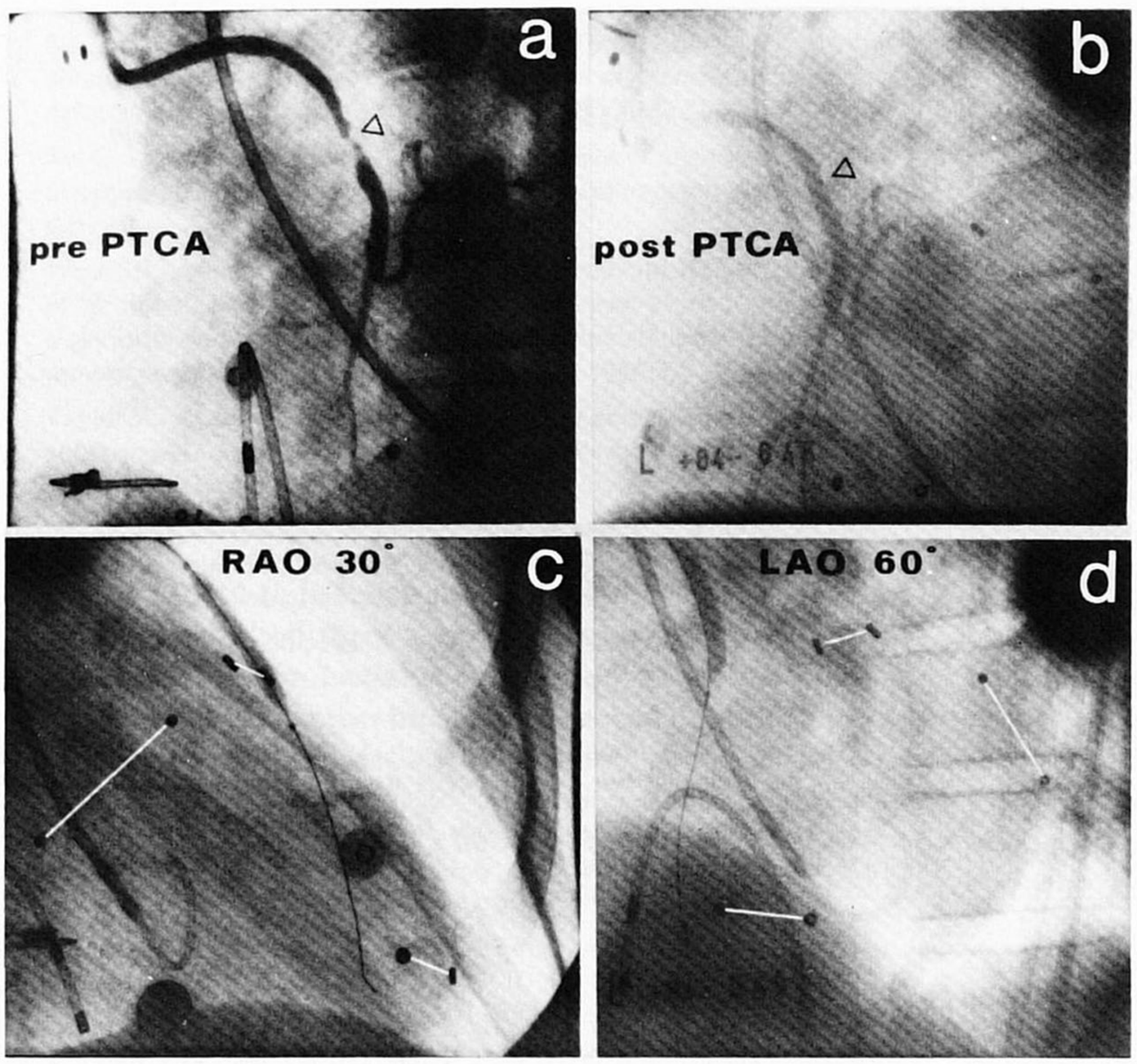

Figure 1. Angiograms of left anterior descending bypass graft stenosis (**arrowhead**) and markers before (**a**) and after (**b**) percutaneous transluminal angioplasty (PTCA). **c** and **d** show the inflated angioplasty catheter in place. LAO = left anterior oblique view; RAO = right anterior oblique view.

enlarged left ventricle (end-diastolic volume index 116 ml/ml^2) with anteroapical and inferior hypokinesia and a global ejection fraction of 0.50. The patient gave informed consent to the investigational part of the angioplasty procedure performed in the left anterior descending bypass graft. The patient's oral medications of beta-receptor blocking and calcium antagonist agents were not discontinued before the procedure.

Methods

Coronary graft angioplasty. An 8F tip manometer pigtail catheter (Millar Instruments) was advanced into the left ventricle. Angioplasty was performed with a 4.2 mm balloon through a 9F Judkins guiding catheter (Schneider) with up to 12 atm of pressure applied. After three dilations with a total occlusion time of 105 seconds, the stenotic pressure gradient decreased from 46 to 9 mm Hg and complete resolution of the angiographic narrowing was achieved (Fig. 1). Then biplane cameras were positioned for a final investigational occlusion (additional occlusion time of 50 seconds). Distal perfusion pressure during the investigational occlusion was 26 mm Hg.

Regional marker motion. Absolute marker separation was determined from radiopaque markers implanted during surgery on the epicardium in each bypassed region as previously described (10). Markers were placed in pairs 2 cm apart and located from 0 to 3 cm distal to each coronary anastomosis transverse to the long axis of the heart (Fig. 1). Synchronized biplane cinefilms (50 frames/s) in 30° right anterior oblique and 60° left anterior oblique views were performed before the placement of the angioplasty catheter (control), during the first 8 seconds of the investigational occlusion (5 minutes after the preceding dilation), 40 seconds after the onset of occlusion and 3 minutes after occlusion. Absolute distances between markers for each marker pair were determined on all frames using a calibration grid. Correction for X-ray film and optical distortion was performed to give true anatomic dimension. To reduce high frequency spatial noise, raw marker length data were filtered with a digital nearest neighbor averaging algorithm. The shortening fraction calculated between these two points (SF_{max} %) was calculated as $(L_{max} - L_{min})/L_{max}$, with L_{max} and L_{min} as the maximal and minimal marker separations, respectively.

Analysis of pressure-derived indexes during systole and diastole. Left ventricular pressure was digitized at 250 samples/s. Left ventricular peak systolic and end-diastolic pressure, peak negative and peak positive rate of rise of pressure (dP/dt) and the relation between (dP/dt)/pressure and pressure linearly extrapolated to pressure = 0 (V_{max}, the maximal velocity of the contractile element) were computed for each measured beat as previously described (11).

Relaxation variables were also computed for each beat from peak negative dP/dt to the previous left ventricular end-diastolic pressure using the semilogarithmic model $P(t) = Po\ e^{-t/T}$, with Po the pressure at peak negative dP/dt when

a true exponential (e) decay is present and T the time (t) constant of relaxation or the time for the best fit pressure curve to decrease from Po to 0.37 × Po (11). In addition, to assess asynchronous relaxation, a biexponential fit for isovolumic relaxation was determined characterized by two exponential time constants (12,13): the fit for the first 40 ms (n = eight samples), T_1; and the fit after the first 40 ms (n = four samples), T_2. When data were fit to single time constant derivative or nonlinear best fit exponential models with pressure offsets (14), derived fits differed significantly from actual data points; therefore, only the semilogarithmic analyses were used.

Results

Each pair of markers was located on a characteristically different part of the ventricle. The markers in the left anterior descending artery distribution (rings) were in the poststenotic territory and showed the most dynamic changes with graft occlusion (Fig. 2 and 3). The second marker pair (beads), distal to the occluded bypass graft on the obtuse marginal branch, was located in a region that showed initial paradoxic motion (similar to the late occlusion motion in the poststenotic territory) and was unaffected by the occlusion. The final pair of markers (bars), located in the left circumflex artery distribution, exhibited an initially abnormal and complex motion that became paradoxic during occlusion. The marker pair of interest in the poststenotic territory was further analyzed and therefore only data from its region are presented.

Changes in regional epicardial wall motion (Fig. 2 and 3). In this transiently ischemic zone, epicardial wall motion before the angioplasty procedure showed a biphasic systolic shortening pattern similar to what we refer to as the W phenomenon. At the onset of the investigational occlusion, epicardial wall motion had significantly changed with loss of this biphasic W pattern. With coronary graft occlusion, the earliest change in shortening occurred at beat 4 after the onset of occlusion and was manifested as a decrease in the shortening fraction from 17.2 to 16.8%. Beats 6 through 8 again manifested the late systolic to early diastolic W pattern seen before angioplasty, but at a higher initial segment length. Fractional shortening decreased further to 11.9% secondary to a decrease in minimal marker separation. During the first seconds of ischemia, the extent of shortening, but not the early systolic velocity of shortening was affected (Fig. 4). Initial segment shortening persisted beyond peak negative dP/dt and thus occurred during isovolumic relaxation. With early ischemia, early diastolic shortening after late systolic lengthening occurred after the onset of peak negative dP/dt and during isovolumic relaxation up to the minimal diastolic pressure.

During late occlusion (40 seconds after onset), the ischemic zone showed a paradoxic lengthening throughout systole beyond the point of the initial end-diastolic length followed by an early diastolic shortening below the level of end-diastolic length. After angioplasty, ischemic zone wall motion returned to its onset configuration with a fractional shortening of 17.8%. The diastolic pressure curve was shifted upward and to the right during occlusion.

Changes in global left ventricular function (Table 1). Heart rate did not change during the graft occlusion. Peak positive dP/dt and peak systolic pressure gradually decreased, accompanied by an increase in left ventricular minimal and end-diastolic pressure. Peak negative dP/dt also decreased during the occlusion, accompanied by a change in its isovolumic pressure decrease such that it was better characterized by a biexponential model of relaxation.

Discussion

The time course and magnitude of changes in global variables of left ventricular function after coronary graft occlusion in this patient are similar to those previously re-

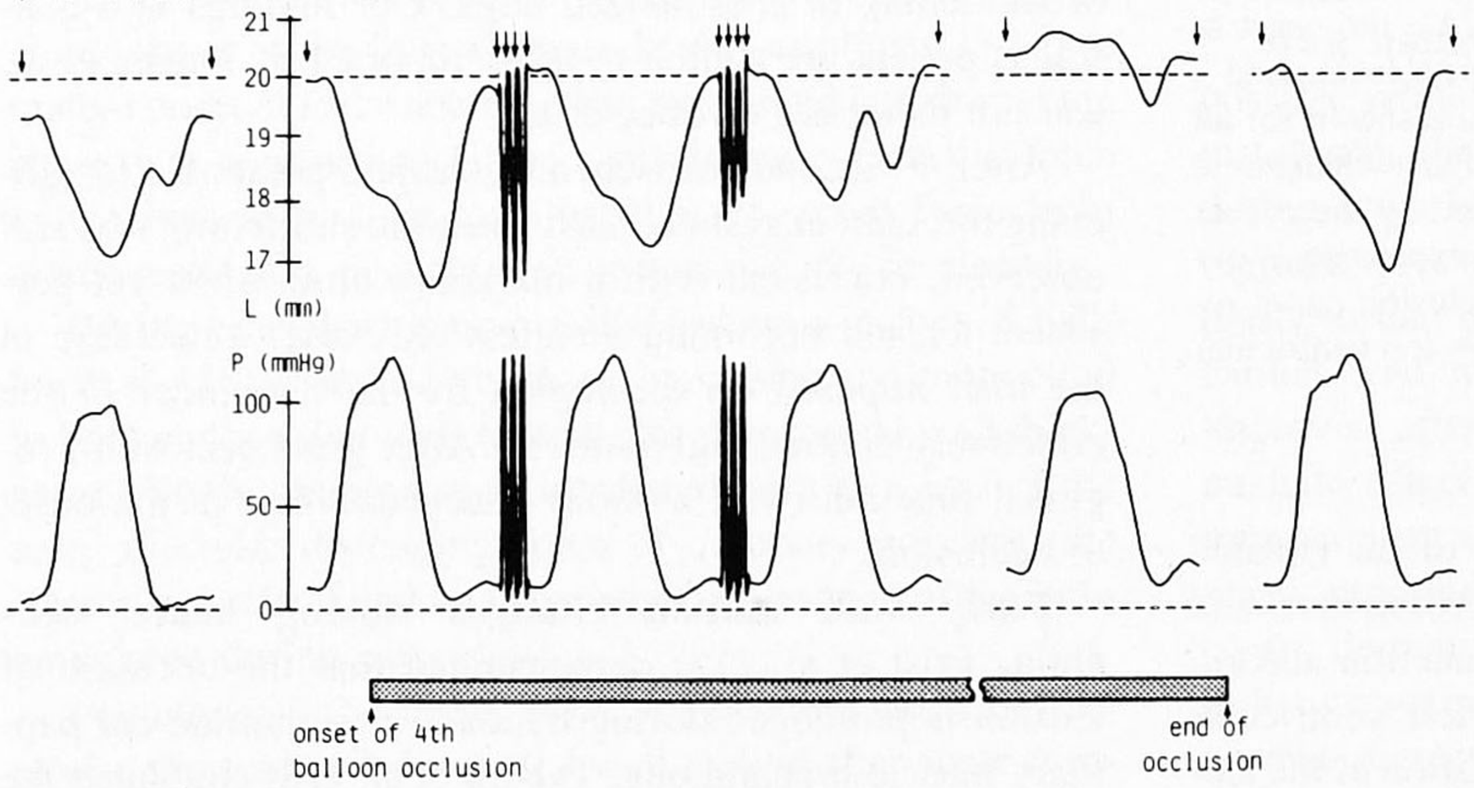

Figure 2. Changes in epicardial marker pair shortening in the region of the coronary bypass graft and left ventricular pressure with graft occlusion. Before angioplasty (PTCA), the marker pair showed abnormal late systolic lengthening and early diastolic shortening. Similar changes were evident in beats 6 to 8 after occlusion (the W phenomenon) (see text).

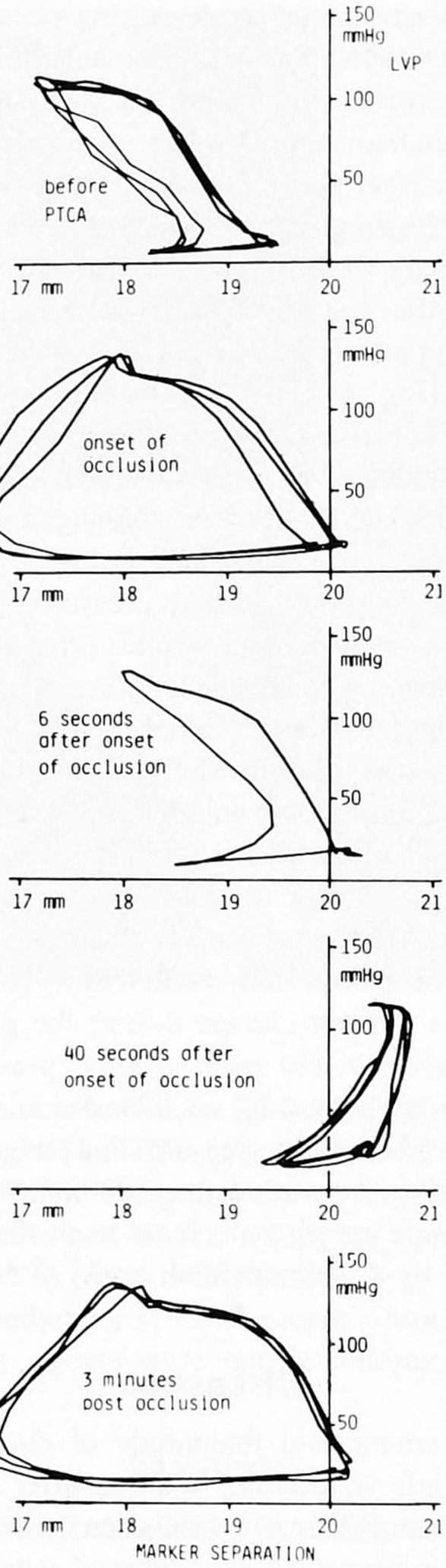

Figure 3. Changes in epicardial pressure-length relation with coronary graft occlusion. Pressure epicardial marker pair distance relations are shown for before angioplasty (PTCA), the onset of occlusion, 6 seconds of occlusion, 40 seconds of occlusion and 3 minutes after occlusion; three consecutive beats are shown for all except the one beat at 6 seconds of occlusion. Early changes in epicardial pressure-length relations are exemplified by the curves after 6 seconds of occlusion. Paradoxic systolic expansion is evident after 40 seconds of occlusion. The postocclusion curve returns to that immediately before occlusion. LVP = left ventricular pressure.

ported in patients undergoing angioplasty of an isolated stenosis of a native coronary artery (6). Progressive and gradual decreases in variables of systolic function accompanied very early changes in the rate of left ventricular pressure decay. The biexponential approximation of the isovolumic pressure decrease is consistent with asynchrony of regional myocardial contraction or relaxation (12). Changes in variables of isovolumic pressure decrease were most pronounced during the first half of occlusion and slightly less at the end of occlusion. In this case, the earliest change in epicardial wall motion was a decrease in the extent of shortening while velocity of early shortening was maintained. These results are similar to the earliest changes of motion of left ventricular mid-wall ultrasonic crystals observed during ischemia in conscious dogs reported by Pagani et al. (1). In contrast, Forrester et al. (4) observed isovolumic systolic lengthening of mercury-in-Silastic epicardial length gauges accompanying the onset of a decrease in the extent of shortening in anesthetized dogs. Our findings in a conscious patient are similar to those reported by Pagani et al. and not those of Forrester et al.

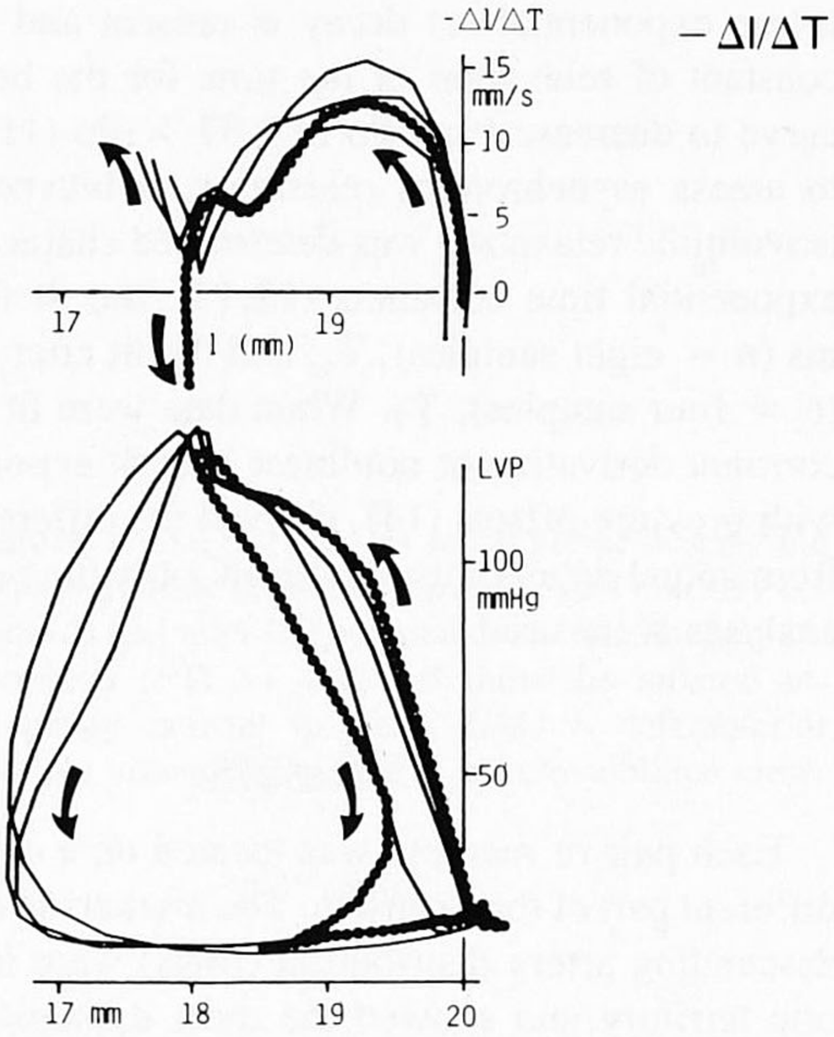

Figure 4. Early changes in velocity-length ($\Delta l/\Delta T$) and pressure-length (**lower graph**) relations with coronary graft occlusion. The early change in epicardial shortening is characterized by a decrease in the extent of shortening with a preservation in the velocity of shortening. Onset of occlusion beats in **solid lines**; 6 seconds after occlusion beat in **solid circles**. LVP = left ventricular pressure.

After 40 seconds of ischemia, despite paradoxic lengthening throughout systole, early diastolic shortening was still observed, consistent with a markedly diminished yet persistent tension becoming manifest only after a decrease in the load imposed on the region by the remainder of the effectively contracting ventricle. After graft occlusion, regional function (wall motion) returned to that at the onset of occlusion.

Early wall motion changes during acute ischemia. Frist et al. (15) demonstrated that the decrease of tension is prolonged during hypoxia in euthermic cat papillary muscle preparations. Tyberg et al. (16) simulated the

Table 1. Global Left Ventricular Function During Coronary Graft Angioplasty

Beat	Preceding RR Interval (ms)	LV Sys (mm Hg)	LV EDP (mm Hg)	+dP/dt (mm Hg/s)	V_{max} (s^{-1})	−dP/dt (mm Hg/s)	T (ms)	T_1 (ms)	T_2 (ms)
Onset of occlusion									
−2	760.0	133.0	17.0	1293.0	39.1	−1162.0	−56.0	−70.0	−47.0
−1	760.0	133.0	17.0	1269.0	39.1	−1154.0	−60.0	−75.0	−49.0
0	764.0	133.0	17.0	1305.0	40.1	−1114.0	−61.0	−77.0	−48.0
1	764.0	132.0	16.0	1276.0	39.3	−1141.0	−59.0	−76.0	−49.0
2	768.0	133.0	17.0	1258.0	38.6	−1120.0	−60.0	−76.0	−50.0
3	772.0	134.0	17.0	1268.0	38.1	−1133.0	−60.0	−78.0	−51.0
4	780.0	133.0	18.0	1275.0	39.1	−1127.0	−61.0	−75.0	−51.0
5	772.0	133.0	18.0	1275.0	37.7	−1106.0	−62.0	−75.0	−52.0
6	772.0	129.0	16.0	1190.0	38.2	−1160.0	−59.0	−74.0	−50.0
7	768.0	129.0	18.0	1177.0	38.4	−1139.0	−64.0	−78.0	−56.0
8	768.0	128.0	18.0	1197.0	37.3	−1109.0	−66.0	−79.0	−56.0
9	768.0	124.0	18.0	1148.0	37.0	−1087.0	−66.0	−80.0	−56.0
10	760.0	120.0	18.0	1147.0	37.1	−1058.0	−66.0	−81.0	−54.0
11	752.0	115.0	16.0	1096.0	37.6	− 990.0	−66.0	−84.0	−53.0
12	752.0	117.0	18.0	1063.0	36.5	− 982.0	−69.0	−90.0	−58.0
13	760.0	116.0	18.0	1065.0	34.5	− 960.0	−71.0	−95.0	−58.0
14	748.0	114.0	18.0	1051.0	35.5	− 902.0	−69.0	−95.0	−56.0
15	744.0	111.0	16.0	1021.0	37.2	− 891.0	−66.0	−96.0	−52.0
40 seconds of occlusion	724.0	115.0	24.0	940.0	24.4	− 867.0	−71.0	−89.0	−60.0
	724.0	114.0	23.0	977.0	24.3	− 894.0	−70.0	−89.0	−58.0
After occlusion	756.0	134.0	20.0	1295.0	41.4	−1087.0	−64.0	−80.0	−55.0
	752.0	132.0	20.0	1297.0	39.4	−1110.0	−61.0	−77.0	−50.0

+dP/dt and −dP/dt = peak positive or negative left ventricular maximal rate of rise of pressure; LV EDP = left ventricular end-diastolic pressure; LV Sys = left ventricular systolic pressure; T, T_1, T_2 = time constants of relaxation for mono- and biexponential models; V_{max} = velocity of the contractile element extrapolated to 0 pressure.

effects of asynchronous contraction and relaxation by analyzing a pair of hypoxic and normal papillary muscles in series. Phasic changes in individual tension-length relations in both muscles were observed.

Wiegner et al. (17) extended these observations by simulating normal papillary muscle with a computer-controlled tension generator in series with a hypoxic papillary muscle. A biphasic pattern of motion of the hypoxic muscle was observed analogous to the W phenomenon in the regionally ischemic zone in the intact left ventricle. The early lengthening phase of the hypoxic muscle was attributed to a premature onset of force decrease and the second late shortening phase was ascribed to either a persisting contractile force of the muscle or to a manifestation of stored force from elastic recoil of previously stretched passive muscle elements.

During graded acute myocardial ischemia in dogs, Smalling et al. (18) observed a biphasic expansion and contraction in both endocardial wall motion and myocardial wall thickening. These changes were attributed both to a loss of the early diastolic distending force of coronary pressure (the "erectile" effect) and to a persistent contraction of the ischemic zone during early diastole.

In summary, the late systolic lengthening and early diastolic shortening in epicardial wall motion after acute coronary occlusion are probably secondary to the early onset of tension decrease in the ischemic region, with tension, however, persisting secondary to a prolonged rate of decrease. Early diastolic contraction may be secondary to passive elastic rebound forces with or without the contribution of persistent active tension. The absence of the "erectile" properties of coronary blood flow may allow more pronounced early diastolic shortening. The relation of these mechanical events to the intracellular biochemical events of activation and relaxation is unknown.

Wall motion abnormalities in chronic ischemia. A possible relation between the wall motion abnormalities at rest during chronic ischemia and those transiently observed during acute ischemia is suggested by the similarity in the regional pressure-length relation before coronary angioplasty to that of beats 7 to 9 after occlusion. Regional epicardial wall motion in this ischemic zone was certainly improved after the first three dilations, although this immediate effect should not be equated with the sustained improvement in systolic and diastolic function after angioplasty reported by others (19,20). Sasayama et al. (8) recently demonstrated an inward motion of left ventricular ischemic segments accompanied by an outward motion of normal segments during isovolumic relaxation in patients

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with chronic angina. This motion was attributed to both persisting contractile activity and elastic recoil of passive elements within the ischemic muscle. In these patients, however, a late systolic expansion of ischemic segments preceding early diastolic contraction was not observed.

Whether a relation exists between abnormal left ventricular relaxation and left ventricular rapid diastolic filling is uncertain. In patients with coronary artery disease, prolongation of the monoexponential time constant of relaxation has been shown to correlate with an increase in minimal left ventricular pressure and to correlate inversely with early diastolic ventricular inflow rate and inflow volume (21). Increases in the time constant of isovolumic relaxation have also been associated with increases in the left ventricular diastolic constant of elastic chamber stiffness during both acute coronary occlusion (22) and exercise-induced angina (23).

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