Electrocardiographic ST-Segment Elevation and Changes in Regional Work of the Left Ventricle during Coronary Angioplasty

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ABSTRACT
The purpose of this study was to evaluate the reduction in regional work of the left ventricle caused by acute myocardial ischemia during coronary angioplasty, and to correlate it with ST-segment elevation. Regional work of the left ventricular myocardium, which is derived from a stress - strain loop, is a useful index of the function of diseased hearts. However, the effects of transient ischemia on the regional work of the myocardium have not been fully elucidated. The subjects consisted of 25 patients who had proximal left anterior descending artery stenosis with normal wall motion and without collateral circulation. The patients were classified as showing ST-segment elevation \( \geq 0.2 \text{ mV} \) (group A, 10 patients), or ST-segment elevation \( < 0.2 \text{ mV} \) (group B, 15 patients) during coronary angioplasty. Group A showed a greater reduction in regional work of the interventricular septum than group B. Regional work recovered to the baseline level 30 seconds after balloon deflation in group B but 40 seconds after in group A. A greater ST elevation during balloon inflation was associated with a greater, prolonged reduction of work performance in the ischemic region and a greater concomitant increase in the opposite nonischemic region.

Key Words: Left ventricular regional work; Stress - strain relation; Percutaneous Transluminal Coronary Angioplasty; Electrocardiographic ST-segment elevation
As coronary blood flow is abruptly interrupted during percutaneous transluminal coronary angioplasty (PTCA), transient regional myocardial ischemia is induced by this procedure. Therefore, PTCA is a useful procedure for studying the effects of acute regional myocardial ischemia on left ventricular (LV) function.

Regional myocardial work has been demonstrated to be useful in analyzing regional dysfunction of the left ventricle in patients with coronary artery disease. We applied the method of calculating regional myocardial work proposed by Nakano and Sugawara et al. Their method is based on the simultaneous measurements of LV pressure and LV regional wall thickness, and gives regional work normalized to unit volume of myocardium in true unit of work (mil/cm²).

The purpose of this study was to assess the change in regional work of the LV wall and correlate it with ST-segment elevation during PTCA to the proximal left anterior descending artery.

Methods

Patients

Twenty-five patients (18 men and 7 women; age (mean ± SD), 62 ± 10 years) with stable angina pectoris were recruited in this study. They were scheduled for PTCA to a significant stenosis in the proximal left anterior descending artery. All patients had single-vessel coronary artery disease without angiographic evidence of collateral circulation and with normal wall motion assessed by both two-dimensional echocardiography and left ventriculography. Patients with unstable angina, recent or previous myocardial infarction, arrhythmia (atrial fibrillation, etc.), valvular diseases, or other cardiac diseases were excluded. Moreover, patients with systemic diseases (hypertension, diabetes mellitus, etc.) which would influence cardiac function were also excluded. All of the patients underwent exercise ⁴⁰⁶-TI myocardial scintigraphy which confirmed that they had myocardial ischemia in the left anterior descending artery region. No patients received beta-adrenergic blocking agents, calcium channel blocking agents, or other cardiovascular drugs within 24 hours before the study. We explained the content of the study to all of the patients and written informed consent was obtained from them.

Electrocardiogram (ECG)

A twelve-lead ECG was monitored and recorded continuously on paper at a speed of 25 mm/s before, during and after balloon deflation. A standard 12-lead electrocardiogram was recorded, except for V2 and V3 leads which were slightly below the usual location because of the simultaneous recording of echocardiography. Calibration was performed at the beginning of the procedure (1 mV = 10 mm). ST-segment elevation was measured at 80 ms after the J point.

Angiography

Coronary angiography and left ventriculography were performed in the usual fashion within several days before PTCA. Left ventriculography was performed in the 30° right anterior oblique view by injection of 30 ml of contrast medium at a rate of 12 ml/s and LV ejection fraction was calculated using the area-length method. Coronary angiography was performed in multiple views with preadministration of nitroglycerin. Severity of stenosis was measured in the following manner. The single angiographic view showing the stenosis with its most severe narrowing was selected and manually traced. Coronary artery diameter was measured with calipers and ruler by an observer.
without knowledge of other study results and then the percent diameter reduction was calculated. Presence or absence of collateral filling of the LAD was assessed from angiograms obtained during contrast injection of the right coronary artery performed before the PTCA procedure. Collaterals were considered absent when diagnostic angiography showed no collateral circulation.

**Angioplasty Procedure and Study Protocol**

Six hours before PTCA, continuous intravenous drip infusion of a low-tension electrolyte solution (Soldem 3A, Terumo, Tokyo, Japan, 150 to 200ml/hour) was begun, and 4 hours before PTCA, continuous intravenous infusion of nitroglycerin (0.5 to 1.0 μg/kg/min) was started. An 8F guiding catheter was positioned in the ostium of the left coronary artery using Judkins’ technique. Nonionic contrast medium (Omnipaque, Nycomed, Oslo, Norway) was used to avoid a myocardial depressant effect during coronary angiography. Hemodynamic measurements were performed without contrast-medium injection.

Balloon inflation was performed three to five times for each patient with a standard coronary angioplasty balloon catheter. Each inflation was performed for 60 seconds after an interval of 1 min for hemodynamic recovery. The mean balloon inflation pressure was 7±2 atmospheres. The mean balloon size was 3.0±0.5 mm. Dilatation was considered successful if the residual stenosis was assessed as smaller than 50% by quantitative coronary angiography.

**Regional Work of the Left Ventricle**

A 6F micromanometer-tipped catheter (Millar SPC-464 D; Houston, TX, USA) was inserted into the left ventricle through the femoral artery to measure LV pressure, and echocardiography was performed using a phased-array scanner (Hewlett Packard, Boston, USA) with a 2.5 MHz transducer. The transducer was placed at the third or fourth intercostal space at the left sternal border, and a short axis view of the left ventricle at a level just above the mid-papillary muscle was obtained. The M-mode cursor was positioned centrally on the two-dimensional image of the short-axis cross section of the left ventricle, and the derived M-mode image was recorded. LV pressure was also recorded simultaneously on the M-mode echocardiogram at a paper speed of 100 mm/s (Fig. 1 top). The data were collected every 10 seconds. LV pressure and epi- and endocardial surfaces were traced carefully with a hand-controlled cursor (Fig. 1 bottom). These tracings were scanned and fed into a computer system (Apple Power Macintosh 8100/80; Cupertino, CA, USA), and LV pressure (P), LV short-axis internal diameter (D), and the thickness (H) of the ventricular septum and the posterior wall were digitized over one cardiac cycle. The data were sampled at 40 points during one cardiac cycle. Therefore, if one cardiac cycle is 1 sec, the sampling interval is 25msec. The stress – strain relations for the ventricular septum and the posterior wall were delineated (Fig. 2). The area surrounded by the stress – strain loop during a cardiac cycle is equal to regional work per unit volume of myocardium. If the loop rotates counterclockwise, the region performs positive work. If the loop rotates clockwise, the region performs negative work; that is, the work is done on the region by the surrounding myocardium.

For simplicity, we used a spherical model of the left ventricle to calculate mean wall stress. The stress (σ) was defined as PD/4H, and the strain was defined as ln (1/H) (the natural logarithm of the reciprocal of wall thickness), which is equivalent to area strain of the midwall layer.

**Statistical Analysis**
We tested sequential changes in LV diameter, pressure and regional work during balloon inflation by repeated-measures analysis of variance (ANOVA). Comparisons of mean changes in groups A and B were performed using a two-way ANOVA and post hoc tests. All other data were compared using Student’s t-test. A probability value of less than 0.05 was considered significant. All data were expressed as mean ± SD.

Results
The patients were classified as showing ST-segment elevation ≥ 0.2mV (group A, 10 patients), or ST-segment elevation < 0.2mV (group B, 15 patients) during PTCA. No complications related to the coronary angioplasty procedure were noted in any of the patients.

Group A and group B
Group A consisted of 7 men and 3 women aged 64 ± 10 years. Group B consisted of 11 men and 4 women aged 61 ± 10 years. LV ejection fraction was 70 ± 4% in group A and 67 ± 5% in group B. Severity of coronary stenosis before PTCA was 83 ± 7% in group A and 85 ± 6% in group B. After PTCA, the mean residual stenosis was 15 ± 12% in group A and 17 ± 14% in group B. No statistically significant differences were found between the two groups.

Electrocardiographic Study
ST-segment elevation was 0.27 ± 0.06 mV in group A and 0.03 ± 0.02 mV in group B. In group A, severe ST-segment elevation (≥ 0.3mV) was observed in 2 of 10 patients and moderate ST-segment elevation (0.3 > ST ≥ 0.2mV) was seen in the other 8 patients. In group B, however, no ST-segment elevation was recognized in 15 of 15 patients and mild ST-segment elevation (0 < ST < 0.1mV) was revealed in the other 5 patients.

The time required for the maximum shift of the ST-segment was 38 ± 15 seconds in both groups. After balloon deflation, the ST elevation returned to normal level within 35 ± 9 seconds in group A and 31 ± 11 seconds in group B patients, respectively. No statistically significant differences were found between the two groups.

LV Dimension (Fig. 3)
The baseline value of LV end-diastolic dimension was 47 ± 6 mm in group A and 48 ± 4 mm in group B. End-diastolic dimension was significantly increased within 40 seconds after balloon inflation (p < 0.05) and was 54 ± 5 mm in group A and 51 ± 4 mm in group B at 60 seconds after balloon inflation. Following balloon deflation, end-diastolic dimension decreased and recovered to the baseline value at about 30 seconds after deflation. At 60 seconds after deflation, end-diastolic dimension in group A was significantly smaller than the baseline value (44 ± 5 mm, p < 0.05).

The baseline value of LV end-systolic dimensions was 29 ± 4 mm in group A and 30 ± 4 mm in group B. End-systolic dimension increased immediately after balloon inflation, and was 44 ± 4 mm in group A and 37 ± 3 mm in group B at 60 seconds after balloon inflation. The end-systolic dimension of group A at this time was significantly larger than that of group B (p < 0.05). End-systolic dimension recovered to the baseline value at about 30 seconds after deflation. At 50 seconds after deflation, end-systolic dimension in group A was significantly lower than the baseline value (26 ± 3 mm, p < 0.05).

LV Pressure (Fig. 4)
The baseline level of LV end-diastolic pressure was 10 ± 4 mmHg in group A and 10 ± 3 mmHg in group B. End-diastolic
pressure increased within 40 seconds of balloon inflation in group A and within 50 seconds in group B, and rose to 18±4 mmHg in group A and 14±3 mmHg in group B at the end of 60 seconds inflation. From the end of inflation to 10 seconds after balloon deflation, the end-diastolic pressure of group A was significantly higher than that of group B (p<0.05). After balloon deflation, end-diastolic pressure decreased and went back to the baseline level at 30 seconds after deflation in group B and 40 seconds after deflation in group A. Overshooting drop of end-diastolic pressure below the baseline level was not seen.

The baseline level of LV end-systolic pressure was 131±15 mmHg in group A and 132±17 mmHg in group B. End-systolic pressure decreased within 30 seconds after inflation, and was 110±14 mmHg in group A and 117±13 mmHg in group B at the end of 60 seconds' inflation. After balloon deflation, end-systolic pressure increased, and returned to the baseline level at 20 seconds after deflation. No statistically significant differences were found between the two groups. In group A, from 50 to 60 seconds after deflation, end-systolic pressure was significantly higher than the baseline level (135±13 mmHg at 50 seconds, p<0.05). In group B, however, no sign of rebound above the baseline level was observed.

**Stress - Strain Relation (Fig. 5 and 6)**

Figure 5 shows original recordings of LV pressure and M-mode echocardiogram (top), tracings of epi- and endocardial surfaces and LV pressure (middle), and the stress-strain loops (bottom) in a patient from group A. The figures on the left represent the data before balloon inflation. The middle figures show those at 60 seconds after inflation, and the figures on the right express those at 30 seconds after deflation. The stress-strain loop of the interventricular septum became extremely narrow, and that of the LV posterior wall became a little broader at 60 seconds after inflation. The loop of the interventricular septum went back to the baseline condition at 30 seconds after balloon deflation.

Figure 6 shows the data from a group B patient. The stress-strain loops changed in the same manner as in Fig. 5. However, changes in the stress-strain loops were smaller in group B than in group A.

**LV Regional Work (Fig. 7)**

The baseline value of regional work of the interventricular septum was 5.6±0.8 mJ/cm² in group A and 5.7±0.7 mJ/cm² in group B. In both groups, regional work of the interventricular septum began to decrease significantly as early as 10 seconds after balloon inflation, and fell to 0.5±0.3 mJ/cm² in group A and 2.0±0.4 mJ/cm² in group B at the end of 60 seconds of inflation. From 20 seconds after inflation to 20 seconds after deflation, the regional work of the interventricular septum was significantly lower in group A than in group B (p<0.05). After balloon deflation, the septal regional work increased, and recovered to the baseline value at 30 seconds after deflation in group B and at 40 seconds after deflation in group A. At 50 seconds after deflation, the septal regional work in group A was significantly higher than its baseline value (6.0±0.8 mJ/cm², p<0.05). In group B, however, no rebound pattern above the baseline level was observed.

The baseline value of the regional work of the posterior wall was 6.1±1.0 mJ/cm² in group A and 6.3±0.8 mJ/cm² in group B. The regional work of the posterior wall increased within 40 seconds of balloon inflation in group A and 60 seconds of balloon inflation in group B, and reached 7.2±1.2 mJ/cm² in group A and 6.6±0.9 mJ/cm² in group B at 10 seconds after deflation. Subsequently, the posterior wall regional work decreased, and recovered to
the baseline value at 30 seconds after deflation in group B, but it had not recovered within 60 seconds after deflation in group A (6.4 ± 0.9 mJ/cm²).

Existence of Collateral Circulations during Balloon Inflation

We encountered subjects who did not show the electrocardiographic change during coronary angioplasty. We performed contralateral angiography during balloon inflation in four of these patients, and observed good collateral circulation from the right coronary artery to the left anterior descending artery, although we had not observed collateral circulation at the time of diagnostic angiography.

Discussion

Electrocardiographic ST-segment changes have attracted much attention in terms of the evaluation of ischemic heart disease. Reversible ST-segment elevation has been considered to reflect transient transmural ischemia. Many investigators have attempted to evaluate the regional contractile state during PTCA, but there is only one study which evaluated the changes in regional work during PTCA in one patient. Our results indicate that there is a significant difference in LV regional function between patients with marked ST-segment elevation and those with negligible ST-segment elevation during acute left anterior descending artery occlusion by PTCA.

Rebound of Regional Function with Reperfusion

We witnessed a transient rebound of regional work above the baseline level with balloon deflation in group A.

Distant et al. evaluated changes in regional LV function by two-dimensional echocardiography in patients with

vasosplastic angina. In 45% of the episodes of vasospastic angina, a transient overshoot in contraction of the ischemic region was recognized after resolution of coronary vasospasm.

Wohlgenannter et al. reported that balloon deflation and subsequent reperfusion of the myocardium brought about the recovery of regional wall motion to the baseline level within 70 seconds in all patients; however, evidence of rebound of regional wall motion to above the baseline level was seen in only 21% of the patients.

The reactive hyperemic response of coronary blood flow may be the cause of the rebound. Serruys et al. observed coronary hemodynamic responses during balloon inflation and recognized that great cardiac vein flow increased by 55% to 91% after reperfusion. Rothman et al. reported that great cardiac vein flow increased by 30% to 59% after reperfusion.

LV Regional Work

In the present study, we used the concept of regional work derived from the relation between mean wall stress and strain (the natural logarithm of the reciprocal of wall thickness) proposed by Sugawara et al. The value of the regional work is normalized to unit volume of myocardium; therefore, the results obtained from hearts of differing size and wall thickness can be compared.

In each patient, the reduction in LV regional work induced by myocardial ischemia was always ahead of changes in the electrocardiogram, LV dimension and LV pressure. This result suggests that reduction in LV regional work may be one of the sensitive indices of myocardial ischemia.

Limitations

The accuracy of this method of calculating regional work is limited by the accuracy in determining the mean wall stress, as discussed in detail in the original papers on this method. When regional ischemia develops, local deformities may occur in the affected area. In this case, the
assumption that the whole ventricle is spherical may include a certain amount of error. Theoretically, it is possible to improve the accuracy of the method by assuming a region of the ventricular wall to be locally spherical. The method can be applied to that region locally without any modification. For this purpose, however, it is necessary to measure the radius of local curvature of the ventricular wall. No simple methods for measuring the radius of curvature continuously throughout a cardiac cycle are available. Therefore, this improvement of the method has not been attempted yet.

To substitute In (1/H) for area strain of the midwall layer, we used the assumption that the myocardium is incompressible throughout one cardiac cycle. Edwards et al. reported that the mass (volume) of the defined cube of myocardium decreased significantly after 30 seconds of coronary occlusion; however, the mass of the defined cube remained constant throughout the cardiac cycle in both control and ischemic states. Incompressibility of the myocardium during a cardiac cycle was also reported by other authors. Therefore, we consider that the accuracy of our method of calculating regional work is not affected by slow changes in myocardium volume during the course of ischemia.

Conclusions
A greater ST elevation during balloon inflation was associated with a greater, prolonged reduction of work performance in the ischemic region and a greater concomitant increase in the opposite nonischemic region. This is the first study to demonstrate these findings with an energetically rigorous dimension of regional work.

References


Fig. 1  Top: Simultaneous recordings of LV pressure and M-mode echocardiogram from a normal subject. Bottom: One cardiac cycle tracings of LV pressure and epi- and endocardial surfaces of the interventricular septum and posterior wall.
IVS = interventricular septum, PW = posterior wall of the left ventricle, LVP = left ventricular pressure.

Ventricular septum

Posterior wall

Mean wall stress

\[ \sigma - \ln \left( \frac{1}{H} \right) \] (N/m²)

Area strain [ln (1/H)]

Fig. 2  The mean wall stress - natural logarithm of the reciprocal of wall thickness [\( \sigma - \ln \left( \frac{1}{H} \right) \)] loops obtained from a normal subject.

The dotted line indicates the LV posterior wall loop and the solid line represents the ventricular septal one. The area enclosed by a \( \sigma - \ln \left( \frac{1}{H} \right) \) loop during a cardiac cycle gives regional work per unit volume of myocardium. The mean wall stress (\( \sigma \)) was defined as DP/4H, and the strain (\( \varepsilon \)) was defined as ln (1/H).
Fig. 3 Changes in LV dimension.
During PTCA, LV end-diastolic dimension (LVDd) and end-systolic dimension (LVDs) were significantly increased. After balloon deflation, the dimensions decreased and returned to the baseline levels. A rebound of LVDd and LVDs below the baseline value were seen in group A. *; p<0.05 vs. pre-inflation, #; p<0.05 vs. group B

Fig. 4 Changes in left ventricular pressure.
LV end-systolic pressure (ESP) decreased and end-diastolic pressure (EDP) increased after balloon inflation. After balloon deflation, the pressures returned to the baseline levels. A rebound of ESP above the baseline value was seen in group A.
*; p<0.05 vs. pre-inflation, #; p<0.05 vs. group B
Fig. 5 Changes in left ventricular pressure and M-mode echocardiogram (top), and the stress ($\sigma$)-strain ($\varepsilon$) loops (bottom) during PTCA in a group A patient.
Left: before balloon inflation. Middle: at 60 seconds after balloon inflation. Right: at 30 seconds after balloon deflation.

Fig. 6 The same changes as in Fig. 5 in a group B patient. The changes in wall motion, LV pressure and the $\sigma$-$\varepsilon$ loop were smaller than those in group A.
Fig. 7 Changes in LV regional work.

Regional work of the interventricular septum (IVS) decreased immediately after balloon inflation. After balloon deflation, the regional work increased, and returned to the baseline level at 30 seconds after balloon deflation in group B and at 40 seconds in group A. A rebound of the regional work above the baseline value was seen in group A. The regional work of the posterior wall (PW) reached its maximum at 10 seconds after balloon deflation. After that the regional work decreased, but did not recover to the baseline level even at 60 seconds after deflation. *, p<0.05 vs. pre-inflation, #, p<0.05 vs. group B.