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

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This study evaluated the reduction in regional work of the left ventricle caused by acute myocardial ischemia during coronary angioplasty, and correlated 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 a diseased heart. 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 ≥ 0.2 mV (group A, 10 patients), or ST-segment elevation < 0.2 mV (group B, 15 patients) during coronary angioplasty. Group A showed a greater reduction in the regional work of the interventricular septum than group B. Regional work recovered to the baseline level 30 s after balloon deflation in group B, but took 40 s 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. (*Jpn Circ J* 2001; 65: 150–154)

Key Words: Left ventricular regional work; Percutaneous transluminal coronary angioplasty; Stress–strain relation; ST-segment elevation

Because coronary blood flow is abruptly interrupted during percutaneous transluminal coronary angioplasty (PTCA), the patient experiences transient regional myocardial ischemia with this procedure. Therefore, PTCA is useful for studying the effects of acute regional myocardial ischemia on left ventricular (LV) function.

Regional myocardial work is used to analyze regional dysfunction of the LV in patients with coronary artery disease (CAD)^{1–4} and in the present study we used the method proposed by Nakano and Sugawara et al^{1–9} which is based on the simultaneous measurement of LV pressure and LV regional wall thickness to give regional work normalized to unit volume of myocardium in true unit of work (mJ/cm³).

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 (LAD).

Methods

Patients

Twenty-five patients (18 men, 7 women; age (mean $\pm$ SD), 62 $\pm$ 10 years) with stable angina pectoris were recruited. They were scheduled for PTCA of a significant stenosis in

the proximal LAD. All patients had single-vessel CAD without angiographic evidence of collateral circulation and with normal wall motion assessed by both 2-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) that would influence cardiac function were also excluded. All the patients underwent exercise ²⁰¹Tl myocardial scintigraphy, which confirmed that they had myocardial ischemia in the LAD region. No patients received α -adrenergic blocking agents, calcium channel blocking agents or other cardiovascular drugs within 24 h of beginning the study. We explained the content of the study to all the patients and written informed consent was obtained from them.

Electrocardiogram (ECG)

A 12-lead ECG monitored and recorded continuously on paper at a speed of 25 mm/s before, during and after balloon deflation. It was a standard 12-lead ECG except for leads V₂ and V₃, 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 several days before PTCA. Left ventriculography was performed in the 30° right anterior oblique view by injection of 30 ml of contrast medium

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Fig 1. (Top) Simultaneous recordings of LV pressure (LVP) 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 (IVS) and posterior wall (PW).

at a rate of 12 ml/s and the LV ejection fraction (LVEF) 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 at its most severe 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. The 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, 150–200 ml/h) was begun, and 4 h before PTCA continuous intravenous infusion of nitroglycerin ($0.5\text{--}1.0\mu\text{g}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) 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.

Balloon inflation was performed 3–5 times for each patient with a standard coronary angioplasty balloon catheter. Each inflation was performed for 60 s after an interval of 1 min for hemodynamic recovery. The mean balloon inflation pressure was 7 ± 2 atmosphere. The mean balloon size was 3.0 ± 0.5 mm. Dilatation was considered successful if the residual stenosis was assessed as less 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 LV through the femoral artery to measure LV pressure, and echocardiography was performed using a phased-array scanner (Hewlett

Fig 2. The mean wall stress–natural logarithm of the reciprocal of wall thickness [$-\ln(1/H)$] 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 $-\ln(1/H)$ loop during a cardiac cycle gives regional work per unit volume of myocardium. The mean wall stress () was defined as $DP/4H$, and the strain () was defined as $\ln(1/H)$.

Packard, Boston, MA, 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 LV just above the mid-papillary muscle was obtained. The M-mode cursor was positioned centrally on the 2-dimensional image of the short-axis cross-section of the LV, 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). The data were collected every 10 s. LV pressure and the epi- and endocardial surfaces were traced carefully with a hand-controlled cursor (Fig 1). 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 posterior wall were digitized during one cardiac cycle. The data were sampled at 40 points during one cardiac cycle. Therefore, if one cardiac cycle is 1 s, the sampling interval is 25 ms. 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 LV to calculate mean wall stress. The stress () 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.^{1–9}

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 2-way ANOVA and post hoc tests. All other data were compared using Student's t test. A p value of less than 0.05 was considered significant. All data were expressed as mean $\pm$ SD.

Results

The patients were classified as either showing ST-segment elevation ≥ 0.2 mV (group A, 10 patients), or ST-

Fig 3. Changes in LV dimension. During PTCA, the LV end-diastolic dimension (LVDd) and the end-systolic dimension (LVDs) were both significantly increased. After balloon deflation, the dimensions decreased and returned to the baseline levels. A rebound of both LVDd and LVDs below the baseline value was 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 (—)–strain (---) loops (Bottom) during PTCA in a group A patient. (Left) Before balloon inflation, (Middle) at 60 s after balloon inflation, (Right) at 30 s 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 — loop were less than those in group A.

segment elevation < 0.2 mV (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 and Group B consisted of 11 men and 4 women aged 61 ± 10 years. The LVEF fraction was $70 \pm 4\%$ in group A and $67 \pm 5\%$ in group B. The severity of coronary stenosis before PTCA was $83 \pm 7\%$ in group A and $85 \pm 6\%$ in group B. After PTCA, the mean residual stenosis was $15 \pm 12\%$ in group A and $17 \pm 14\%$ in group B. No statistically significant differences were found between the 2 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 (≥ 0.3 mV) was observed in 2 of 10 patients and moderate ST-segment elevation ($0.3 > ST \geq 0.2$ mV) was seen in the other 8 patients. In group B, however, no ST-segment elevation was recognized in 10 of the 15 patients and only mild ST-segment elevation ($0 < ST \leq 0.1$ mV) was revealed in the other 5 patients.

The time required for the maximum shift of the ST-segment was 38 ± 15 s in both groups. After balloon deflation, the ST elevation returned to normal level within 35 ± 9 s in group A and 31 ± 11 s in group B patients. No statistically significant differences were found between the 2 groups.

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 s after balloon deflation in group B and at 40 s 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 s after balloon deflation. After that the regional work decreased, but did not recover to the baseline level even at 60 s after deflation. * $p < 0.05$ vs pre-inflation, # $p < 0.05$ vs group B.

LV Dimension (Fig 3)

The baseline value of the LV end-diastolic dimension (LVDd) was 47 ± 6 mm in group A and 48 ± 4 mm in group B, and within 40 s of balloon inflation it was significantly increased ($p < 0.05$) and at 60 s after balloon inflation it was 54 ± 5 mm in group A and 51 ± 4 mm in group B. Following balloon deflation, the LVDd decreased and had recovered to the baseline value approximately 30 s after deflation. At 60 s after deflation, the LVDd in group A was significantly less than the baseline value (44 ± 5 mm, $p < 0.05$).

The baseline value of the LV end-systolic dimension (LVDs) was 29 ± 4 mm in group A and 30 ± 4 mm in group B. It increased immediately after balloon inflation and at 60 s after inflation was 44 ± 4 mm in group A and 37 ± 3 mm in group B, significantly larger in group A than in group B ($p < 0.05$). The LVDs recovered to the baseline value approximately 30 s after deflation and at 50 s after deflation was significantly less than the baseline value in group A (26 ± 3 mm, $p < 0.05$).

LV Pressure (Fig 4)

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

The baseline level of LV end-systolic pressure (ESP) was 131 ± 15 mmHg in group A and 132 ± 17 mmHg in group B. ESP decreased within 30 s after inflation and at the end of 60 s inflation was 110 ± 14 mmHg in group A and 117 ± 13 mmHg in group B. After balloon deflation, ESP increased, and returned to the baseline level at 20 s after deflation. No statistically significant differences were found between the 2 groups. In group A, from 50 to 60 s after deflation, ESP was significantly higher than the baseline level (135 ± 13 mmHg at 50 s, $p < 0.05$). In group B, however, no sign of rebound

above the baseline level was observed.

Stress-Strain Relation (Figs 5 and 6)

Fig 5 shows the original recordings of LV pressure and M-mode echocardiogram, tracings of epi- and endocardial surfaces and LV pressure, and the stress-strain loops from a patient from group A. The stress-strain loop of the interventricular septum (IVS) became extremely narrow, and that of the LV posterior wall became a little broader at 60 s after inflation. The loop of the IVS went back to the baseline condition at 30 s after balloon deflation.

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

LV Regional Work (Fig 7)

The baseline value of regional work of the IVS was 5.6 ± 0.8 mJ/cm³ in group A and 5.7 ± 0.7 mJ/cm³ in group B. In both groups, regional work of the IVS began to decrease significantly as early as 10 s after balloon inflation, and fell to 0.5 ± 0.3 mJ/cm³ in group A and 2.0 ± 0.4 mJ/cm³ in group B at the end of 60 s of inflation. From 20 s after inflation to 20 s after deflation, the regional work of the IVS was significantly lower in group A than in group B ($p < 0.05$). After balloon deflation, the IVS regional work increased, and recovered to the baseline value at 30 s after deflation in group B and at 40 s after deflation in group A. At 50 s after deflation, the IVS regional work in group A was significantly higher than its baseline value (6.0 ± 0.8 mJ/cm³, $p < 0.05$). 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/cm³ in group A and 6.3 ± 0.8 mJ/cm³ in group B. The regional work of the posterior wall increased within 40 s of balloon inflation in group A and 60 s of balloon inflation in group B, and at 10 s after deflation reached 7.2 ± 1.2 mJ/cm³ in group A and 6.6 ± 0.9 mJ/cm³ in group B. Subsequently, the posterior wall regional work decreased, and recovered to the baseline value at 30 s after deflation in group B, but it had not recovered within 60 s of deflation in group A (6.4 ± 0.9 mJ/cm³).

Existence of Collateral Circulations During Balloon Inflation

We encountered subjects who did not show electrocardiographic change during coronary angioplasty and so we performed contralateral angiography during balloon inflation in 4 of them, 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 evaluation of ischemic heart disease because reversible ST-segment elevation are considered to reflect transient transmural ischemia. Many investigators¹⁰⁻¹⁵ have attempted to evaluate the regional contractile state during PTCA, but there is only 1 study that evaluated the changes in regional work during PTCA! 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 LAD 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 al¹⁶ evaluated changes in regional LV function by 2-dimensional echocardiography in patients with vasospastic 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. Wohlgeleit et al¹⁰ reported that balloon deflation and subsequent reperfusion of the myocardium brought about the recovery of regional wall motion to the baseline level within 70 s 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 al¹¹ observed coronary hemodynamic responses during balloon inflation and recognized that great cardiac vein flow increased by 55–91% after reperfusion. Rothman et al¹² reported that great cardiac vein flow increased by 30–59% 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^{1–9}. 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 ECG, LV dimension and LV pressure, which suggests that reduction in LV regional work may be one of the sensitive indices of myocardial ischemia.

Study Limitations

The accuracy of the method of calculating regional work is limited by the accuracy in determining the mean wall stress, as discussed in detail in the original reports^{2,9}. When regional ischemia develops, local deformities may occur in the affected area; therefore, 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 and then the method can be applied to that region without any modification. For this purpose, however, it is necessary to measure the radius of local curvature of the ventricular wall and currently there are not any simple methods for measuring the radius of curvature continuously throughout a cardiac cycle. Therefore, this improvement of the method has not been attempted yet.

To substitute $\ln(1/H)$ for area strain of the midwall layer, we used the assumption that the myocardium is incompressible throughout one cardiac cycle. Edwards et al¹⁷ reported that the mass (volume) of the defined cube of myocardium decreased significantly after 30 s 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 has also been reported by other authors^{18,19}. Therefore, we consider that the accuracy of our method of calculating regional work was 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 dimensions of regional work.

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