Preclinical research

The sequential changes in myocardial thickness and thickening which occur during acute transmural infarction, infarct reperfusion and the resultant expression of reperfusion injury

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Received 12 February 2003; revised 22 December 2003; accepted 12 January 2004

Aim Successful primary PTCA (with TIMI 3 reflow) in patients with acute transmural infarction has been observed to result in an immediate abnormal increase in wall thickness associated with persisting abnormal post-systolic thickening. To understand the sequential changes in regional deformation during: (i) the development of acute transmural infarction, (ii) upon TIMI grade 3 infarct reperfusion and (iii) during the subsequent expression of reperfusion injury the following correlative experimental study was performed in a pure animal model in which there was no distal dispersion of thrombotic material causing either no reflow or secondary microvascular obstruction.

Methods In 10 closed-chest pigs, a 90 min PTCA circumflex occlusion was used to induce a transmural infarction. This was followed by 60 min of TIMI 3 infarct reperfusion. M-mode ultrasound data from the “at risk” posterior wall infarct segment and from a control remote non-ischemic septal segment were acquired at standardized time intervals. Changes in regional deformation (end-diastolic (EDWT), end-systolic (ESWT) and post-systolic (PSWT) wall thickness, end-systolic strain (\(e_{ES}\)) and post-systolic strain (\(e_{PS}\))) were measured.

Results In this pure animal model of acute transmural infarction/infarct reperfusion (with no pre-existing intra-luminal thrombus), the induced changes in wall thickness and thickening were complex. During prolonged occlusion, after an initial acute fall in ESWT, there was no further change in systolic deformation to indicate the progression of ischaemia to infarction. Both transmurally infarcted and reperfused-infarcted myocardium retained post-systolic thickening indicating that this parameter, taken in...
Introduction

Few clinical studies have examined the sequential changes in regional myocardial deformation during the development of a transmural myocardial infarction and the immediate changes after successful post-PTCA infarct reperfusion and none have, to the authors’ knowledge, examined the changes in both systolic and post-systolic deformation indices with regard to segment viability. In a pilot prospective clinical study into deformation changes following acute infarct reperfusion based on both cardiac ultrasound and cardiac magnetic resonance data we observed that there was a consistent abnormal increase in regional wall thickness in a successfully reperfused infarct zone during the first few days after reperfusion. To understand these clinical observations, an experimental study was undertaken in which a closed chest, closed pericardium PTCA-based model of acute transmural infarction/reperfusion was used. This model represented a “pure” infarct/reperfusion injury model as there was no confounding effect from the presence of pre-existing thrombus in the coronary artery and thus little chance of distal thrombus micro-embolization with resultant areas of microvascular obstruction.

The changes in myocardial deformation induced by acute regional ischemia were first described by Tennant and Wiggers. Among such ischemia-induced changes, post-systolic thickening (PST) (i.e., regional wall thickening after aortic valve closure) is a phenomenon whose pathophysiology remains poorly understood despite being investigated in many prior experimental and clinical studies. Indeed, the persistence of ischemia-related regional PST has been proposed as a clinical marker of viability in chronically ischemic segments and its magnitude has been correlated to the amount of functional recovery after reperfusion of stunned myocardium.

However, virtually all such studies have been based on open-pericardium, collateralized dog models in which the lack of pericardial restraint might have influenced both the measured global and regional function parameters. In addition, the presence of collateral flow in the dog model results in the ischemic substrate produced by coronary occlusion being stunned myocardium rather than transmural infarction. At present, there is thus surprisingly little experimental information on the nature and the time course of changes in regional deformation parameters (including changes in PST) either during the development of a transmural infarction or during acute infarct reperfusion as reperfusion injury is expressed. As M-mode echocardiography is a clinical reference method for the non-invasive measurement of myocardial wall dimensions, high temporal resolution M-mode radio-frequency (RF) data were acquired in the above closed-chest, closed pericardium pig model. The data obtained on regional deformation were compared to changes in global function.

Materials and methods

Animal preparation

Ten domestic pigs, weighting 25–35 kg, were premedicated with Ketamin (10–20 mg/kg IM) and anaesthetized with a combination of Propofol 2% (12–20 mg/kg per hour IV) and Fentanyl (0.5 μg/kg per min). The animals were intubated and ventilated with a mixture of air and oxygen to maintain their arterial blood gas values in the physiologic range. The left main coronary artery was catheterized under fluoroscopic guidance using an 8F Judkins left catheter introduced via the left carotid artery. A percutaneous transluminal coronary angioplasty balloon (3.5 mm) was placed in the mid-segment of the circumflex artery. All animals were treated according to the National Institute of Health Guide for the care and use of laboratory animals.

Acquisition of ultrasonic data

All ultrasound recordings were performed using a Toshiba PowerVision 6000 (Toshiba Medical Systems, Otawara, Japan) equipped with an RF-interface for research purposes. Ultrasound data were acquired in fundamental imaging mode using a 5 MHz phased array transducer (Toshiba, PSM-50AT). M-mode RF data from the remote septal and “at risk” posterior wall segments were acquired using a standard parasternal long-axis view. Data
were taken at a pulse repetition frequency of 5 kHz. The RF datasets thus obtained were both of high temporal and spatial (axial < 1 mm; lateral approximately 4 mm) resolution. All datasets were recorded over 3–5 consecutive heart cycles during a period of brief apnoea. Data were transferred to a PC workstation for off-line analysis.

Experimental monitoring

A continuous 3-lead electrocardiogram was recorded. Left ventricular (LV) pressure (P) and its first temporal derivative (dP/dt) were measured continuously using a micro-manometer-tipped catheter (Millar Instruments, Houston, TX). The above signals were digitized on-line and transferred to a PC workstation with a commercially available software package (Powerlab/Chart, ADInstruments, Mountain View, CA). To avoid acoustic artefacts, care was taken to exclude the catheter from the ultrasonic beam when acquiring ultrasound data.

Experimental protocol

Echocardiographic and haemodynamic data were obtained in the anaesthetized animals both pre- (Pre) and post-instrumentation (Baseline). To identify the myocardial segment "at risk" a series of consecutive brief (20 s) acute coronary artery occlusions per animal were induced by repeatedly inflating and deflating the balloon (8–10 bar pressure). Occlusion and reperfusion datasets were recorded alternately as it was not possible for data storage reasons to record both occlusion and reperfusion RF data continuously from the same short-lived occlusion. This resulted in a total of three occlusion and three reperfusion datasets per animal. The animals were allowed to recover between each short-lived occlusion for a period of either 90 or 150 s, respectively (Fig. 1). Following the short-lived occlusions, reperusions, a total occlusion was induced for a period of 90 min. Ultrasound data were acquired every minute for the first 10 min, every 5 min from 10 to 30 min, and thereafter every 10 min. For reperfusion, the ultrasound datasets were acquired every minute for the first 5 min, every 5 min from 5 to 30 min and every 10 min until one hour of reperfusion. Reperfusion grade (TIMI 1–3) was assessed visually by small hand injections of contrast into the aortic root at least three times during the reperfusion period. Finally, while under deep anaesthesia, the heart was stopped by an intravenous injection of potassium chloride and excised. In 8 pigs, the heart was cut into 1 cm thick horizontal slices by sectioning parallel to the valve plane. These slices were immersed in a triphenyltetrazolium chloride solution to confirm infarct site, size and transmurality. In the 2 remaining pigs, histology was performed. Therefore, these two hearts were perfused with Formalin 5% and immersed in the same solution for 48 h. Subsequently, they were cut into slices as described above and samples taken for histology from the "at risk" basal and apical posterior walls, and from the remote non-infarcted basal and apical walls. All samples were stained with haematoxylin-eosin. The stained specimens were then examined under a microscope (Axioplan, Zeiss, Jena, Germany) using magnifications of 50, 100 and 400.

Data analysis

Standard grey-scale M-mode images were reconstructed from each RF dataset using customized post-processing software (Speqle 4.02b, Catholic University Leuven). Posterior and septal wall dimensions and cavity size were measured at end-diastole (EDWT) and end-systole (ESWT). Moreover, posterior wall dimensions were measured at the time of maximal posterior wall thickness after aortic valve closure (PSWT). End-diastole and end-systole were defined as the onset of the QRS-complex and 20 ms before minimal dP/dt, respectively.14 End-systolic (ES) and post-systolic strain (PS) were calculated as (ESWT – EDWT)/EDWT and (PSWT – ESWT)/ESWT, respectively. Finally, the ejection fraction (EF) was calculated from the M-mode measurements using the Teicholtz equation.

Statistics

All measurements are presented as the means ± SE. The statistical analysis focused on assessing mean changes over time. To take account of the repeated measures, data were analysed using a covariance structure designed for multivariate repeated measures. Following ischemia and reperfusion, the evolution of each parameter over time was assessed by means of statistical modelling. The following functions were assessed in the evaluation of the evolution over time during both conditions: linear, logarithmic, exponential and their inverses. Separate functions were fitted for both conditions. The best model was identified by means of Akaike’s Information Criterion. Adequacy of the model was assessed by performing an appropriate likelihood ratio test. Using this model, the differences of interest were estimated and statistically tested against the null hypothesis of being zero using an approximate F test. All tests were performed at the 5% significance level using the procedure MIXED in SAS (SAS Institute Inc., Cary, NC) version 8.02.

![Fig. 1](https://academic.oup.com/wurheartj/article-abstract/25/9/794/567800) Schematic representation of the experimental protocol. Small vertical lines indicate the time points of data acquisition.
Results

In all 10 animals, either post-mortem myocardial staining or histology confirmed that the posterior myocardial segment had been included in the transmural area “at risk”. Statistical analysis, comparing measurements pre- and post-instrumentation, showed that the processes involved in the initial instrumentation of the animals did not cause significant changes in any of the parameters studied.

Haemodynamic data

The haemodynamic data obtained pre-instrumentation, at baseline, during the short-lived ischemic and reperfusion challenges, and for different time points recorded during the prolonged total occlusion and subsequent reperfusion are shown in Table 1.

Short-lived occlusion/reperfusion series

The heart rate averaged 96 ± 5 bpm at baseline and did not change significantly during the short-lived occlusion/reperfusion series. In contrast to the LVED pressure, the LVES pressure decreased significantly during each of the short-lived ischemic episodes but returned immediately to baseline levels for the two first reperfusion datasets. For the third reperfusion dataset, both LVES and LVED pressure remained significantly reduced for some minutes. dP/dtmax showed a tendency to fall during each of the ischemic episodes. Except for the third occlusion dataset, this fall was however not statistically significant. dP/dtmax did however return to baseline values during reperfusion.

Prolonged occlusion/reperfusion

During the 90 min of coronary occlusion, a slow but continuous increase in heart rate was observed (p < 0.05). At reperfusion, the heart rate showed a tendency to increase further but this did not reach statistical significance. While LVED pressures did not change during the whole experiment, LVES pressures decreased immediately after coronary occlusion but showed a partial recovery during the following 90 min. At reperfusion, LVES pressure abruptly decreased but again showed a partial recovery during the reperfusion period. Finally, during occlusion, dP/dtmax showed a similar behaviour to LVES pressure with an immediate fall after coronary occlusion followed by a partial recovery over the next 90 min. However, during reperfusion, dP/dtmax continued to fall.

M-mode Measurements

Because of the presence of ventricular extra-systoles (mostly occurring during infarct reperfusion), approximately 9% of the RF datasets had to be excluded from deformation analysis. Fig. 2 shows the typical M-mode sequence of changes in regional deformation, which occurred in the “at risk” posterior wall and in the remote, non-ischemic septal wall in all animals.

Table 1 Haemodynamic data (means ± SE) pre-instrumentation, at baseline, during the short-lived occlusions/reperfusions and during the prolonged occlusion and reperfusion studies

<table>
<thead>
<tr>
<th></th>
<th>HR (bpm)</th>
<th>LVESP (mmHg)</th>
<th>LVEDP (mmHg)</th>
<th>dP/dtmax (mmHg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-instrumentation</td>
<td>95 ± 3</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Baseline</td>
<td>96 ± 5</td>
<td>95 ± 6</td>
<td>11 ± 1</td>
<td>1802 ± 139</td>
</tr>
<tr>
<td>20’ Occlusion 1</td>
<td>96 ± 5</td>
<td>85 ± 6*</td>
<td>12 ± 1</td>
<td>1718 ± 136</td>
</tr>
<tr>
<td>20’ Occlusion 2</td>
<td>97 ± 6</td>
<td>86 ± 6*</td>
<td>12 ± 1</td>
<td>1668 ± 96</td>
</tr>
<tr>
<td>20’ Occlusion 3</td>
<td>99 ± 6</td>
<td>82 ± 7*</td>
<td>11 ± 1</td>
<td>1637 ± 119*</td>
</tr>
<tr>
<td>Reperfusion 1</td>
<td>95 ± 5</td>
<td>90 ± 8</td>
<td>11 ± 1</td>
<td>1826 ± 139</td>
</tr>
<tr>
<td>Reperfusion 2</td>
<td>97 ± 6</td>
<td>90 ± 8</td>
<td>11 ± 1</td>
<td>1788 ± 115</td>
</tr>
<tr>
<td>Reperfusion 3</td>
<td>98 ± 6</td>
<td>85 ± 6*</td>
<td>9 ± 1*</td>
<td>1799 ± 123</td>
</tr>
<tr>
<td>1’ Prolonged occlusion</td>
<td>107 ± 7*</td>
<td>74 ± 5*</td>
<td>11 ± 2</td>
<td>1521 ± 127*</td>
</tr>
<tr>
<td>90’ Prolonged occlusion</td>
<td>108 ± 5*</td>
<td>77 ± 6*</td>
<td>11 ± 1</td>
<td>1692 ± 85</td>
</tr>
<tr>
<td>1’ Reperfusion</td>
<td>133 ± 8*</td>
<td>72 ± 4*</td>
<td>9 ± 1</td>
<td>1587 ± 171</td>
</tr>
<tr>
<td>60’ Reperfusion</td>
<td>128 ± 11*</td>
<td>78 ± 3*</td>
<td>10 ± 2</td>
<td>1391 ± 98*</td>
</tr>
</tbody>
</table>

HR, heart rate; LVESP, left ventricular end-systolic pressure; LVEDP, left ventricular end-diastolic pressure; *p < 0.05 vs. baseline; †p < 0.05 vs. 90’ of occlusion; ‡p < 0.05 change within occlusion; §p < 0.05 change within reperfusion.
from baseline during the prolonged occlusion/reperfusion period. Posterior wall EDWT did not change significantly during the occlusion period. However, on reperfusion, EDWT rapidly increased above baseline levels and then continued to thicken over the next 60 min \((p < 0.05)\). Both posterior ESWT and PSWT were significantly reduced after coronary occlusion. While ESWT did not change significantly over the next 90 min, PSWT slowly decreased \((p < 0.05)\). Following reperfusion, both parameters increased immediately \((p < 0.05)\) and then continued to increase further over the next 60 min. PSWT had returned to baseline levels after 1 min of reperfusion and then continued to thicken further while ESWT initially remained significantly reduced, only returning to baseline levels after a few minutes of reperfusion.

Fig. 5 shows changes in septal and posterior \(e_{ES}\) and posterior \(e_{PS}\). Septal \(e_{ES}\) did not change significantly from baseline levels during the whole experiment. In contrast, posterior wall \(e_{ES}\) fell immediately after coronary occlusion but showed no further, statistically significant, change over the occlusion/reperfusion period. With the onset of ischemia, \(e_{PS}\) increased immediately by about 40\%. During the next 90 min, the amount of post-systolic thickening decreased linearly \((p < 0.05)\) but always remained above baseline levels with a persisting \(e_{PS}\) of approximately 25\% after 90 min of ischemia (versus 3\% at baseline). Finally, on reperfusion, the amount of post-systolic thickening stopped decreasing and remained unchanged at the 90 min occlusion level.

The Teicholtz-derived left ventricular EF fell immediately after coronary occlusion but showed a partial recovery during the next 90 min (Fig. 6). During reperfusion, a continuous decrease in EF was observed. Finally, ED cavity size showed a gradual increase during the occlusion period \((p < 0.05)\) resulting in a significantly increased ED cavity after 90 min of ischemia. ED cavity size, as measured by M-mode echocardiography, fell immediately on reperfusion with no further changes occurring over the reperfusion period.
TTC staining and microscopic examination

TTC staining showed the myocardial segments under investigation to be transmurally infarcted in all animals. In both animals in whom histology was available, the basal and apical myocardium “at risk” at a magnification of 100 and 400 showed extensive areas of endo-to-epicardial interstitial oedema which separated blocks of myofibrils (Fig. 7). Under a magnification of 400 the capillaries appeared intact with no thrombotic plugging. There was neither evidence of blood extravasation or haemorrhage nor any confluent necrosis in either of the specimens examined. The corresponding samples from the non-ischemic anterior and septal walls contained only normal myocardium.

Discussion

Either transient or chronic regional myocardial ischemia is known to induce predictable alterations in local myocardial deformation.\textsuperscript{17} \textemdash \textsuperscript{17} The nature and magnitude of these changes have previously been shown to be related to the severity and extent of the ischemia.\textsuperscript{18} \textsuperscript{20} In our experiments, the preliminary series of short-lived occlusions resulted in the myocardial segment of the posterior...
wall “at risk” to show a deformation pattern characteristic of acutely ischemic myocardium, i.e. reduced $\varepsilon_{ES}$ with an associated increase in $\varepsilon_{PS}$.

This pattern was induced by the first vessel occlusion and could be reproduced during subsequent occlusions. These brief occlusions thus proved that the “at risk” segment of the posterior wall could indeed well be visualized during the prolonged occlusion-reperfusion study in a reproducible manner. In fact, for this reason, we had chosen to use the circumflex rather than the left anterior descending coronary artery for balloon occlusion.

**Post-systolic thickening as a marker of viability**

The mechanisms underlying the phenomenon of ischemia-related post-systolic deformation have been the
subject of much debate. Three different explanations have been proposed namely either delayed active contraction, late passive thickening or elastic recoil overshoot after bulging. In our experiment, systolic bulging did not occur as infarct size was relatively small. Thus, the elastic recoil theory could not be applied. Moreover, as ePS persisted after 90 min of coronary occlusion while staining clearly showed the myocardial segment to be transmurally infarcted and therefore all active force development must have ceased, the delayed active contraction theory could not be valid. Our findings thus suggest that in this animal model the late passive thickening theory is the correct one. This would be in concordance with the observed regional differences in end-systolic myocardial wall thickness. The reduction in ePS during the 90 min following coronary occlusion could be explained by an increase in local wall stiffness in the infarcted segment. Indeed, if local differences in end-systolic myocardial wall thickness did not change during the ischemic period, interacting forces attempting to thicken the ischemic (and thinner) myocardium after aortic valve closure, would remain constant (given a constant elasticity of the normally perfused myocardium). However, as this constant interaction force resulted in a systematic reduction of the deformation response, local resistance to deformation, i.e. local stiffness, would necessarily increase. Such an increase in myocardial stiffness with ischemia has previously been described.

Prior investigators have shown that the induction of post-systolic deformation may serve as a sensitive and early marker of the presence of acute or chronic ischemia. Furthermore, both in acute and chronic regional ischemia, the presence of post-systolic thickening has also been associated with sequential viability. In our experiments, it was shown that in the situation of acute total coronary artery occlusion, post-systolic thickening has at least a significant amount of passive deformation to it. In itself, the presence of post-systolic deformation in these substrates can thus not be used as a marker of viability but it should be combined with other functional indices. End-systolic strain and peak systolic strain rate and their responses to a stress test could be useful parameters in this context.

The consequences of reperfusion

With TIMI 3 infarct reperfusion, end-systolic posterior wall thickness returned to baseline within 5 min while end-diastolic wall thickness increased above baseline levels after 1 min. Both wall thickness parameters then continued to increase logarithmically during the 60 min reperfusion period. The corresponding parameters in the non-ischemic septum were not altered by reperfusion.

The observed immediate increase in end-diastolic and end-systolic wall thickness with reperfusion can most probably be explained by a combination of immediate reflow and consequent reactive hyperaemia after the opening of the occluded vessel. It is probable that the returning blood flow combined with the expression of "reperfusion injury" as tissue oedema was responsible for the ongoing logarithmic increase in posterior wall dimensions over time. Prior histology studies have shown that reperfusion injury is associated with tissue oedema, myocyte damage, micro-vascular and endothelial injury and cell necrosis. In the report of Jennings et al., tissue oedema could be detected after 30 s of infarct zone reflow and persisted throughout 20 min of reperfusion following only 15 min of ischemia. Our own histological observations confirmed the consistent finding of marked areas of extravascular tissue oedema separating blocks of myofibrils. However, in this acute model there were no changes of endothelial injury or capillary plugging by thrombosis and platelets. This could be due to...
In this study, we attempted to produce an experimental model of acute transmural infarction with TIMI 3 flow reperfusion, changes in wall thickness and thickening were complex. Both transmurally infarcted and reperfused-infarcted myocardium retained post-systolic thickening. This would imply that the presence of post-systolic thickening cannot be used in isolation as a marker of viability but should be combined with other regional functional indices. The most striking finding was the immediate increase in end-diastolic wall thickness with reperfusion with a further increase over the following 60 min period as reperfusion injury was further...
expressed. The changes in wall thickness were confirmed by histology to be caused by massive extra-cellular oedema.

The identification of an acute increase in regional wall thickness in a reperfused infarct zone by cardiac ultrasound following primary PTCA might thus be used in patients to both identify successful infarct reperfusion and to monitor the presence, extent and resolution of the oedema associated with reperfusion injury.

Acknowledgements

The authors would like to thank Ann Belmans for doing the statistics of this study and Joerg Schiegel of Toshiba Medical Systems for his technical assistance.

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