Quantitative analysis of intraventricular blood flow dynamics by echocardiographic particle image velocimetry in patients with acute myocardial infarction at different stages of left ventricular dysfunction

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Aims

Left ventricular (LV) diastolic filling is characterized by the formation of a vortex that supports an efficient transit into systolic ejection. Aim of this study was to assess the intraventricular (IV) blood flow dynamics among patients with ST elevated myocardial infarction (STEMI) at different degrees of LV dysfunction, in the attempt to find novel indicators of LV pump efficiency.

Methods and results

Sixty-four subjects, 34 consecutive STEMI patients and 30 healthy controls, underwent before hospital discharge 2D speckle tracking echocardiography to assess global longitudinal strain (GLS), and echo-particle image velocimetry analysis to assess flow energetic parameters. Left ventricular volumes ejection fraction (LVEF) and global wall motion score index (GWMSI) were evaluated by 3D echocardiography. STEMI patients were subdivided into three groups according to LVEF. Energy dissipation, vorticity fluctuation, and kinetic energy fluctuation indexes, which characterize the degree of disturbance in the flow, exhibit a biphasic behaviour in STEMI patients when compared with controls, with the highest values in patients with still preserved LV function and progressive lower values with LV function worsening. Significant linear correlations were found between energy dissipation index and both LVEF and GLS ($r = 0.57$, $P < 0.001$ and $r = 0.61$, $P = 0.001$, respectively). Kinetic energy fluctuation index significantly correlates with both LVEF ($r = 0.75$, $P < 0.001$) and GLS ($-0.58$, $P = 0.002$). Finally, a significant correlation was observed between GWMSI and energy dissipation index ($-0.56$, $P = 0.008$).

Conclusions

The present study describes, for the first time, the progression of IV flow energetic properties in patients with acute myocardial infarction at different stages of LV dysfunction when compared with healthy controls. Further data are needed to assess the role of these parameters in the development and maintenance of LV dysfunction.

Keywords

Acute myocardial infarction • Intraventricular flow

Introduction

The assessment of intraventricular (IV) fluid dynamics may be considered as a potential novel indicator of overall cardiac health.1,2 During early diastolic filling, blood flow crossing mitral valve is directed towards the left ventricular (LV) posterolateral wall generating a vortex moving towards the apex; this phenomenon helps blood redirection toward the LV outflow tract and promotes the conservation of kinetic energy from diastole into systole, possibly minimizing energy consumption during systolic ejection.3,4 The physiological
vortex formation is the result of a proper synergy of wall dynamic forces in an asymmetrical cavity of suitable volume. Any disorder of such a natural arrangement may be a concurrent cause of ventricular dysfunction. Diastolic vortices have been previously described and recognized by using flow visualization techniques in vitro models of human heart, or by colour Doppler imaging and magnetic resonance velocity mapping. Particle image velocimetry (PIV), previously used in fluid dynamics for measuring the velocity field from laser-illuminated sheet in turbulent flow fields, has recently adapted to echocardiography (Echo-PIV) for evaluating the instantaneous vortical blood motion into the LV. Two-dimensional harmonic imaging seeded with ultrasound microbubbles contrast agents was used. Swirling intracardiac flow motion is tracked by bubbles and then pro-seeded with ultrasound microbubbles contrast agents was used.

The aim of the present study was to assess, in a series of patients with recent basic study, we described the properties of LV vortices in normal and diseased populations. The Echo-PIV technique has been proven for vascular measurements, verified in a clear experimental setting, and accurately validated utilizing an in vitro model of the LV and compared with laser-based digital PIV. The direction of fluid velocity can be easily detected by using Echo-PIV, whereas high velocities are underestimated. Therefore, this technique permits an accurate evaluation of the vortical motion, which is characterized by relatively low velocities. In a recent basic study, we described the properties of LV vortices in normal hearts using this technique.

The LV vortex minimizes kinetic energy dissipation and facilitates the smooth redirection of blood towards the outflow tract. Preliminary observations have suggested that LV remodelling is associated with an attenuation of the blood flow kinetic energy. The aim of the present study was to assess, in a series of patients with acute ST elevation myocardial infarction (STEMI), how parameters characterizing the LV energetics vary at different stages of LV dysfunction, in the attempt to find novel indicators of LV pump efficiency.

### Methods

#### Study population

The study population consisted of 64 subjects, 34 consecutive patients with first STEMI divided according to LV ejection fraction (LVEF) in three subgroups (Group I, LVEF > 50%, n = 14; Group II, LVEF between 50% and 30%, n = 10; Group III, LVEF < 30%, n = 10) and 30 age-matched (mean age 59 ± 7 years) healthy volunteers. Inclusion criteria in the STEMI population were: (i) typical chest pain lasting >30 min and unresolved by nitroglycerin, (ii) ST segment elevation >0.1 mV in at least two contiguous leads in the initial electrocardiogram, and (iii) elevated markers of myocardial necrosis. Exclusion criteria were: (i) previous myocardial infarction, (ii) previous PCI or coronary artery bypass intervention, (iii) signs of clinical instability, (iv) poor acoustic window, (v) rhythm disturbances, (vi) valve disease or cardiomyopathy, and (vii) blood pressure <100 mmHg. All patients underwent, before hospital discharge, standard 2D and 3D echocardiography, 2D speckle tracking echocardiography (2D-STE) analysis, and contrast echocardiography for Echo-PIV analysis. Left ventricular volumes, LVEF, and global wall motion score index (GWMSI) were evaluated by 3D echocardiography analysis, and contrast echocardiography for Echo-PIV analysis. Left ventricular volumes, LVEF, and global wall motion score index (GWMSI) were evaluated by 3D echocardiography analysis, and contrast echocardiography for Echo-PIV analysis. left ventricular end-diastolic and end-systolic volumes, and ejection fraction were obtained using a semiautomatic border detection technique.

#### Echo-PIV: image analysis

Quantification of LV flow was performed by post-processing 2D contrast-enhanced cine loops with Echo-PIV technique, as previously described. In brief, previously validated experimental software named ‘Hyper Flow’ was used. The echo-PIV quantification method is characterized by a substantial cut-off for the estimation of high velocities because of the insufficient frame rate of the echocardiographic acquisition, although it was demonstrated that the direction of the flow remains estimated with good accuracy. The cut-off limitation affects the flow field only during peak velocity and close to the valve, while the intra-cavity cavity circulation, which is associated with lower velocities, is not influenced. However, to ensure that acquisition settings are not affecting the results, all the subsequent quantifications are expressed in dimensionless terms. For statistical processing, a set of scalar dimensionless parameters related to the flow pattern are defined (see Supplementary data online, methods for mathematical details). These parameters summarize flow properties in the whole LV and over the whole heartbeat. First, parameters characterizing the position and geometry of the vortex were evaluated by analysis of steady streaming (heartbeat-averaged) flow field that can be considered as a sort of fingerprint of the LV flow pattern. The complete mathematical procedure is described in the Supplementary data online, methods and it is briefly recalled here. The compact region representing the vortex is first identified by the steady-streaming stream-function pattern, then the following parameters are computed: the vortex area is the area of region normalized with the LV area; the vortex intensity (sometime called vortex

### Images acquisition protocol

All subjects underwent 2D and 3D echocardiography analysis using a standard commercial ultrasound machine (Philips IE33®) within 5 days after hospital admission, to assess LV function as previously described. In brief, routine 2D images were acquired in the apical four-chamber, apical two-chamber, and apical long-axis views, with a frame rate >60 Hz to perform 2D-ST analysis. Sector width was optimized to allow for complete myocardial visualization while maximizing frame rate. All images were acquired during apnoea, to minimize translation movements of the heart. All subjects underwent ultrasound contrast injection, because the LV fluid dynamics was tracked by acquisition of 2D images in the presence of a light infusion of ultrasound contrast agent (SonoVue®) that is designed and proven to act as a marker seed for the visualization and PIV quantification of blood motion. In this study, we performed exams using a continuous pump infusion of contrast agent at slow infusion rate (0.5 mL/min), acquiring images with a frame rate of 80 Hz. This procedure was designed to ensure that neither a lack of bubbles nor saturation was found in the chamber as required for PIV to properly work. Acquisitions for flow analysis are performed in the apical three-chamber view in order to appreciate the blood motion from the inlet to the outflow, assuming that the flow on such a plane is representative of the overall LV fluid dynamics. The flow sequence during one entire heartbeat, recorded by Echo-PIV, is shown in Figure 1. Transthoracic harmonic real-time 3D echocardiography was then performed from the apical four-chamber view using the full-volume technique. Wide-angle acquisition was performed, and a high frame rate (30 ± 4 Hz) was obtained using the seven-beat acquisition protocol, in which seven consecutive wedge-shaped sub volumes are consecutively sampled with a trigger to the R-wave of the electrocardiogram. At least three acquisitions were obtained for each subject and analysed offline using commercially available software (QLAB version 7.0; Philips Medical Systems). Left ventricular end-diastolic and end-systolic volumes, and ejection fraction were obtained using a semiautomatic border detection technique.
circulation) is the integral of the vorticity—i.e. flow rotation—contained in the vortex region, normalized with the total swirling in the LV (i.e. the integral of the vorticity, in absolute value, inside the entire LV); the vortex depth, the distance of the vortex centre from the mitral base, and the vortex length along the base-apex direction, are both normalized with the LV length. Secondly, the geometric description was integrated with a quantification of the energetic properties of the flow (see Supplementary data online, methods for mathematical details) that were summarized into additional dimensionless parameters: the energy dissipation index represents the amount of kinetic energy dissipated for friction during the entire heartbeat; it is normalized with the average kinetic energy to provide a dimensionless index indicating the amount of loss of kinetic energy relative to that available. Ideally, the higher the energy loss, the lower is the efficiency of the system. The kinetic energy fluctuation index and the vorticity fluctuation index are the standard deviation of kinetic energy and of squared vorticity, normalized with the corresponding average values. They are informative of the degree of regularity in the flow (or, loosely speaking, of turbulence). In addition, vortex formation time (VFT) was calculated from ejection fraction with two proportional- ity coefficients (one given by the percentage contribution of the early filling, E-wave, to the total diastolic; the second as a shape factor given by the ratio between the end-diastolic volume and that of a sphere with diameter equal to that of the mitral valve). This parameter, widely discussed in the past, is assumed to provide a measure of the optimization of the diastolic vortex formation process on the basis of the transmural flow property. Finally, an estimation of the direct flow (Vdirect), the volume of blood entered during diastole that transits directly into aorta within the following systole, was also calculated and expressed as a

Figure 1: This figure shows frame by frame the formation of intraventricular vortices during an entire cardiac cycle in a normal control. The velocity vectors (yellow arrows) and the vortex extension (blue = clockwise, red = counterclockwise) inside the left ventricle are shown superimposed to the echographic image. The sequence shows (left to right, top to bottom) the intraventricular non-static flow during isovolumic relaxation (IVR) followed by the mitral jet of rapid filling (RF) that enters into the cavity with counter-rotating vortices on the two sides. During diastasis, the vortices move towards the apex and the counterclockwise dissipates at the wall to leave one clockwise rotation slowly weakening, whose intensity may vary among individuals. This diastolic circulation is further fed during the atrial systole by the mitral jet eventually giving rise to a clockwise LV circulation during isovolumic contraction (IVC). As a result of diastolic filling, blood flow is naturally directed towards the outflow track and then enters into systole without discontinuity.
percentage of the end-diastolic volume. This parameter describes the quality of blood transit in the LV from the inlet to the outlet. This was estimated here from the 2D velocity field obtained by echo-PIV. It was previously introduced in 3D cardiac magnetic resonance, 15,21 then employed in 3D echography-based numerical simulations, 22 and more recently introduced in 2D echography with a different Doppler-based reconstruction of the 2D velocity field 23 (see Supplementary data online, methods for mathematical details).

2D-STE: images analysis

A 16-segment model was used to subdivide the LV for subsequent analysis. The digital loops were stored and analysed by the vendor-independent 2D CPA (Cardiac Performance Analysis-Tomtec GmbH, Munich, Germany) software for frame-by-frame movement of stable patterns of speckle, as previously described. 16 In brief, the endocardial borders were traced at the end-systolic frame from the three apical views and they were analysed in the successive frames during cardiac cycle. Longitudinal global strain (GLS) was obtained by averaging all segmental peak systolic strain values in a 16-segment model.

Statistical analysis

Statistical analysis was performed with the SPSS software package for Windows v. 16.0 (SPSS Inc., Chicago, IL, USA). All categorical variables are expressed as percentages and all continuous variables as mean ± SD. The differences between categorical variables were analysed by the \( \chi^2 \) test. The differences between continuous variables were analysed

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### Table 1  Clinical characteristics of STEMI population

<table>
<thead>
<tr>
<th></th>
<th>Group I (n = 14)</th>
<th>Group II (n = 10)</th>
<th>Group III (n = 10)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male sex, % (n)</td>
<td>71 (10)</td>
<td>80 (8)</td>
<td>100 (10)</td>
<td>0.20</td>
</tr>
<tr>
<td>Hypertension, % (n)</td>
<td>50 (7)</td>
<td>60 (6)</td>
<td>50 (5)</td>
<td>0.39</td>
</tr>
<tr>
<td>Smoking habit, % (n)</td>
<td>50 (7)</td>
<td>60 (5)</td>
<td>60 (6)</td>
<td>0.47</td>
</tr>
<tr>
<td>Diabetes, % (n)</td>
<td>8 (1)</td>
<td>10 (1)</td>
<td>20 (2)</td>
<td>0.10</td>
</tr>
<tr>
<td>Hyperlipidaemia, % (n)</td>
<td>50 (7)</td>
<td>60 (6)</td>
<td>50 (5)</td>
<td>0.38</td>
</tr>
<tr>
<td>Age, % (n)</td>
<td>60 ± 12</td>
<td>56 ± 7.9</td>
<td>57 ± 8.2</td>
<td>0.39</td>
</tr>
<tr>
<td>BSA (m²)</td>
<td>1.9 ± 0.1</td>
<td>1.6 ± 0.7</td>
<td>2.0 ± 3.4</td>
<td>0.08</td>
</tr>
<tr>
<td>SBP (mmHg)</td>
<td>126 ± 15</td>
<td>115 ± 11</td>
<td>122 ± 4.2</td>
<td>0.17</td>
</tr>
<tr>
<td>DBP (mmHg)</td>
<td>76 ± 6</td>
<td>73 ± 14</td>
<td>72 ± 3.4</td>
<td>0.25</td>
</tr>
</tbody>
</table>

BSA, body surface area; SBP, systolic blood pressure; DBP, diastolic blood pressure.

Group I: patients with LVEF > 50%, Group II: patients with LVEF between 50 and 30%, and Group III: patients with LVEF < 30%.

### Table 2  Coronary angiography data

<table>
<thead>
<tr>
<th></th>
<th>Group I (n = 14)</th>
<th>Group II (n = 10)</th>
<th>Group III (n = 10)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single vessel disease,% (n)</td>
<td>58 (8)</td>
<td>40 (4)</td>
<td>33 (3)</td>
<td>0.41</td>
</tr>
<tr>
<td>Multi vessel disease,% (n)</td>
<td>42 (6)</td>
<td>60 (6)</td>
<td>67 (7)</td>
<td>0.41</td>
</tr>
<tr>
<td>LAD culprit, % (n)</td>
<td>50 (7)</td>
<td>50 (5)</td>
<td>70 (7)</td>
<td>0.99</td>
</tr>
<tr>
<td>RCA culprit, % (n)</td>
<td>33 (5)</td>
<td>30 (3)</td>
<td>20 (2)</td>
<td></td>
</tr>
<tr>
<td>LCx culprit % (n)</td>
<td>16 (2)</td>
<td>20 (2)</td>
<td>10 (1)</td>
<td></td>
</tr>
</tbody>
</table>

LAD, left anterior descendent; RCA, right coronary artery; LCx, left circumflex artery.

Group I: patients with LVEF > 50%, Group II: patients with LVEF between 50 and 30%, and Group III: patients with LVEF < 30%.

### Table 3  Echocardiographic data

<table>
<thead>
<tr>
<th></th>
<th>Group I (n = 14)</th>
<th>Group II (n = 10)</th>
<th>Group III (n = 10)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLS</td>
<td>−16 ± 5.3</td>
<td>−13 ± 6.7</td>
<td>−8 ± 4.2</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>LVEDVi (mL/m²)</td>
<td>53 ± 15</td>
<td>54 ± 26</td>
<td>60 ± 12</td>
<td>0.045</td>
</tr>
<tr>
<td>LVESVi (mL/m²)</td>
<td>24 ± 7.7</td>
<td>30 ± 18</td>
<td>46 ± 9.2</td>
<td>0.032</td>
</tr>
<tr>
<td>GWMSI</td>
<td>1.7 ± 0.6</td>
<td>2.2 ± 0.9</td>
<td>3.3 ± 1.8</td>
<td>0.008</td>
</tr>
</tbody>
</table>

GLS, global longitudinal strain, LVEDVi, left ventricular end-diastolic volume index, LVESVi, left ventricular end-systolic volume index, GWMSI, global wall motion score index.

Group I: patients with LVEF > 50%, Group II: patients with LVEF between 50 and 30%, and Group III: patients with LVEF < 30%.
Table 4  Intraventricular flow parameters

<table>
<thead>
<tr>
<th></th>
<th>Controls (n = 30)</th>
<th>Group I (n = 14)</th>
<th>Group II (n = 10)</th>
<th>Group III (n = 10)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vortex area</td>
<td>0.34 ± 0.08</td>
<td>0.35 ± 0.07</td>
<td>0.35 ± 0.09</td>
<td>0.33 ± 0.09</td>
<td>0.42</td>
</tr>
<tr>
<td>Vortex length</td>
<td>0.77 ± 0.5</td>
<td>0.7 ± 0.1</td>
<td>0.68 ± 0.14</td>
<td>0.64 ± 0.09</td>
<td>0.38</td>
</tr>
<tr>
<td>Vortex depth</td>
<td>0.4 ± 0.1</td>
<td>0.37 ± 0.1</td>
<td>0.45 ± 0.11</td>
<td>0.46 ± 0.054</td>
<td>0.25</td>
</tr>
<tr>
<td>Vortex intensity</td>
<td>−0.44 ± 0.1</td>
<td>−0.43 ± 0.2</td>
<td>−0.43 ± 0.23</td>
<td>−0.37 ± 0.26</td>
<td>0.58</td>
</tr>
<tr>
<td>Energy dissipation index*</td>
<td>0.52 ± 0.22</td>
<td>0.67 ± 0.29</td>
<td>0.46 ± 0.21</td>
<td>0.33 ± 0.09</td>
<td>0.008</td>
</tr>
<tr>
<td>Vortex fluctuation index**</td>
<td>0.80 ± 0.03</td>
<td>0.83 ± 0.06</td>
<td>0.75 ± 0.16</td>
<td>0.60 ± 0.07</td>
<td>0.024</td>
</tr>
<tr>
<td>Kinetic energy fluctuation index***</td>
<td>1.55 ± 0.23</td>
<td>1.83 ± 0.54</td>
<td>1.40 ± 0.54</td>
<td>0.74 ± 0.22</td>
<td>0.004</td>
</tr>
<tr>
<td>Vortex formation time****</td>
<td>4.43 ± 1.35</td>
<td>2.52 ± 1.4</td>
<td>1.65 ± 0.64</td>
<td>2.33 ± 0.94</td>
<td>0.034</td>
</tr>
<tr>
<td>Vdirect</td>
<td>59.67 ± 36.9</td>
<td>54.9 ± 15.9</td>
<td>43.17 ± 28.1</td>
<td>43 ± 2</td>
<td>0.659</td>
</tr>
</tbody>
</table>

Group I: patients with LVEF > 50%, Group II: patients with LVEF between 50 and 30%, and Group III: patients with LVEF < 30%.

*P = 0.045 (healthy subjects vs. Group I), P = 0.043 (Group I vs. II), P = 0.001 (Group I vs. III).

**P = 0.03 (Group I vs. II), P = 0.002 (Group I vs. II), P = 0.005 (Group II vs. III).

***P = 0.03 (healthy subjects vs. Group I), P = 0.01 (Group I vs. II), P = 0.005 (Group I vs. III), P = 0.008 (Group II vs. III).

****P = 0.029 (control group vs. Group II).

Figure 2: STEMI population: (A) correlation between left ventricular ejection fraction (LVEF) and energy dissipation; (B) LVEF and kinetic energy fluctuation; (C) global longitudinal strain (GLS) and LVEF; (D) GLS and kinetic energy fluctuation.
by the non-parametric Mann–Whitney test and Kruskal–Wallis test and a post hoc analysis with Mann–Whitney was made for differences in inter-groups. To assess changes of blood flow kinetic energy at progressive degree of LV of regional and global dysfunction, flow parameters and LVEF, GLS, and WMSI were correlated by Spearman’s linear regression analysis. A two-tailed P-value of < 0.05 was considered statistically significant.

**Results**

All STEMI patients underwent primary PCI within 6 h from symptom onset. No differences in baseline clinical and angiographic characteristics between STEMI groups were found (Tables 1 and 2). As for the study design, LVEF was significantly reduced between groups; accordingly, graded changes in LV volumes, GWMSI, and in global strain were detected (Table 3).

**Intraventricular flow analysis**

All flow parameters were depicted in Table 4. Significant differences between groups were found for following flow data: (i) energy dissipation index (0.52 ± 0.22 in controls, 0.67 ± 0.29 in Group I, 0.46 ± 0.21 in Group II, and 0.33 ± 0.09 in Group III, P = 0.008), (ii) vorticity fluctuation index (0.80 ± 0.03 in controls, 0.83 ± 0.06 in Group I, 0.75 ± 0.16 in Group II, and 0.60 ± 0.07 in Group III, P = 0.024), and (iii) kinetic energy fluctuation index (1.55 ± 0.23 in controls, 1.83 ± 0.54 in Group I, 1.40 ± 0.54 in Group II, and 0.74 ± 0.22 in Group III, P = 0.004).

Vortex formation time was significantly higher in the control group (P = 0.034, P-value between controls and Group II, 0.029). Vdirect did not show any significant difference among groups.

**Relationship between IV flow parameters and LV function in STEMI population**

Significant linear correlations were found between LVEF and both energy dissipation and kinetic energy fluctuation indexes (r = 0.57, P < 0.001, and r = 0.75, P < 0.001, respectively), and between GLS and both energy dissipation kinetic and energy fluctuation indexes (r = −0.61, P < 0.001, and r = −0.58, P = 0.002, respectively) (Figure 2A–D). Finally, a significant correlation was found between GWMSI and energy dissipation index (r = −0.56, P = 0.004).

**Discussion**

The present study describes, for the first time, the energetic properties of IV flow in patients with acute myocardial infarction at different stages of LV dysfunction when healthy controls. The highest energy dissipation was observed in STEMI patients with still preserved global LV function; such increased energy consumption with respect to controls witnesses the extra effort to maintain adequate pump efficiency. Further data are needed to understand if, after a certain degree of energy dissipation and vortex kinetics fluctuation indexes, this compensatory mechanism becomes excessively expensive or generate a discomfort that may favour progressive LV dysfunction at follow-up. A progressive weakening of IV flow dynamic was observed as LV dysfunction develops, demonstrating a close relationship with LV pumping function. The vortex dynamics abnormalities are an integrated result of physiopathological conditions affecting both the mechanical properties of the LV wall segments (active and passive) and ventricular size and shape. In this context, changes of the physical parameters characterizing the IV vortices energetics seem to be very sensitive markers of LV dysfunction.

**Intraventricular flow dynamic and LV function**

The correct sequence of vortex development results from the interaction between flow and anatomical cardiac structures. The abnormal pathway of blood flow in areas of LV dysfunction may be one of the mechanisms of thrombus formation. Further, physiological vortex propagation during diastole may be beneficial in avoiding turbulence and keep energetic dissipation within normal values. Previous studies showed that patients undergoing mitral valve replacement showed a reversal of the vortical flow inside the left ventricle and higher energy dissipation, caused by the redirection of the mitral jet after surgery. In line with this issue, we demonstrated an alteration in LV flow also in patients with acute myocardial infarction, due to the presence of injured myocardial wall segments. The alteration in energetic parameters is not accompanied by significant changes in flow transit properties, probably more intimately related to changes in vortex properties than to flow energetics. However, differences could be imputable to the direct flow calculation from 2D Echo-PIV that is not accurate enough.

The abnormal tissue dynamics found in the early phase after STEMI immediately reflects into abnormalities in vortex formation resulting in a biphasic behaviour: a significant (Table 4) increased energy consumption and vortex kinetics with respect to healthy conditions in STEMI patients with still preserved global LV function and a significant progressive decrease in energy consumption and in vortex dynamics in STEMI patients at different stages of LV dysfunction (Figure 3). Thus,
energy dissipation exhibits two opposite patterns: in patients with small infarct size, as detected by WMA extent, and relatively preserved LVEF, LV filling-emptying process is associated with development of a multiplicity of conflicting vortices: turbulence. The fluctuation of kinetic energy or vorticity, other indicator of the degree of irregularity in the intracardiac flow, increases as a consequence of sharp and repeated flow peaks established in the presence of turbulence. This IV turbulence reflects, in fluid dynamics terms, the small irregularities in myocardial contraction, and energy dissipation increases as a consequence of the extra-effort to maintain a normal LV function. The small increase in LV volumes, detected in the first days in this subset of STEMI patients, augments the stroke volume by the Starling mechanism so that a near normal cardiac output is ensured. Therefore, early post-infarct remodelling could be beneficial and promotes survival, as early adaptive mechanisms: on the other hand, this is achieved at the expense of a higher energy dissipation of IV vortices. Infarcted myocardial segments, although still contracting, introduce disequilibrium in the time coherence of the LV whole motion that, coupled with an increased regional stiffness, give rise to an abnormal vortex formation and propagation. This condition could be teleologically seen as the attempt of the system to ensure, at least in basal conditions, an adequate cardiac output before volumetric and structural changes develop. As described in previous theoretical studies, energy dissipation is particularly

Figure 4: Patient with acute myocardial infarction and LVEF = 45%. During rapid filling (RF), flow entering into the ventricle is not aligned with the LV major axis, and produces an irregular blood motion during diastasis with small vortices interacting one with another without a coherent recirculating pattern; the following atrial systole interacts with an irregular flow and blood motion during isovolumic contraction (IVC) does not show the proper pre-ejection pattern. These vorticity fluctuations, typical of turbulent flows, are associated with enhanced dissipation of kinetic energy (energy dissipation = 0.88) (see Supplementary data online, Movie S1).
high if there are rapid changes in vorticity or in presence of turbulence. High fluctuations in vorticity and kinetic energy, as observed in this class of patients, are associated with high energy dissipation values. More longitudinal data are needed to understand if, after a certain degree of energy dissipation and vortex kinetics fluctuation, this compensatory mechanism becomes very expensive and may favour adverse remodelling at follow-up.

Conversely, in patients with larger infarct size, more impaired LV function, and more dilated LV, a significant reduction in energy dissipation was observed. This opposite behaviour could be explained by the lower energetic field of a more damaged left ventricle with a non-adequate cardiac output and it could be related to the absence of rapidly changing vortices with a poor kinetic energy fluctuation. Nucifora et al. previously demonstrated by measuring the VFT that larger infarctions are associated with a more severe alteration in LV intracavitary blood flow dynamics. We confirm a reduction in VFT in patients when compared with controls. In addition, the energetic parameters permit to differentiate the different stages of disease. Supporting this hypothesis, we observed the presence, in severely impaired ventricles, of a single vortex, occupying the centre of the ventricle and non-interacting with others (Figures 4 and 5; Supplementary data online, Movies S1 and S2). In line with this issue, we demonstrated that energy dissipation and flow turbulence were directly correlated with LVEF and GLS, considered a more sensitive index of LV systolic function. However, flow energetic indexes also differentiated patients from controls with similar LVEF (Figure 3).

A recent study showed that heart failure patients with preserved LVEF present a less coherent vortex formation process, when compared with controls, whereas patients with reduced LVEF present a weaker but coherent vortical arrangement. These observations are in agreement with the present findings, and confirm how sustaining a proper LVEF with an improper myocardial contraction reflects in an inharmonious flow, requiring extra energetic expenditure. However, the actual energy lost inside the LV cavity is very small.

![Figure 5: Patient with acute myocardial infarction and LVEF = 25%. The flow is characterized by a single, central vortex during the whole heartbeat, strengthening during diastole and weakening during systole, persisting up to isovolumic relaxation (IVR), weakly interacting with others flow features. This stable flow pattern is associated with small fluctuations and low energy dissipation (energy dissipation = 0.27) (see Supplementary data online, Movie S2).](image_url)
when compared with that dissipated along the entire systemic circulation. Whether it is globally relevant or not, the presence of higher dissipation and turbulent fluctuation witnesses a loss of normal physiological function. This improper energetics is on one side a measurable consequence of the disease, and on another it also witness a discomfort at the organ level and could represent a stimulus for heart adaptation. An abnormal, sub-optimal LV function is an index of cardiac health. Proc Natl Acad Sci 2006;103:6305–8.


Study limitation

The most important limit of our study is the small population observed. Therefore, results should be considered as a preliminary suggestion and must be verified in larger and varied cohorts. Another limitation is the lack of follow-up data, which are in course of acquisition. The Echo-PIV analysis presents some limitation; in particular, as previously discussed, it may underestimate high velocities. Further, Echo-PIV analyses flow by using 2D imaging, thus flow dynamics in the entire cavity cannot be visualized and only flow visible on the scan plane was analysed. Thus, IV flow tracking may be affected by the out-of-plane flow motion. Care was taken to consider a scan plane crossing both the mitral and aortic valve, approximately representative of the gross flow properties and minor secondary flow; nevertheless, the possibility of missing important 3D flow features remains. However, the relative low frame rate of 3D echo imaging does not allow at moment a correct analysis of IV flow dynamics.}

Conclusion

Our preliminary data show that STEMI patients with preserved LV function exhibit a significant increase in energy dissipation when compared with controls, suggesting the presence of a new fluid-tissue dynamical balance as compensatory mechanisms for maintaining an adequate LVEF. In the presence of a significant LV dysfunction, energy dissipation is markedly reduced as a consequence of a low flow kinetic energy. If these results were confirmed, serial monitoring of energy dissipation changes over time may allow quantitative information on LV pump efficiency. Further data are needed to assess the role of these parameters in the development and maintenance of LV dysfunction.

Supplementary data

Supplementary data are available at European Heart Journal – Cardiovascular Imaging online.

Conflict of interest: None declared.

References


A 48-year-old man was transferred in cardiogenic shock after an acute anterolateral myocardial infarction. Inotropic support could not achieve enough improvement in haemodynamic status; the microaxial pump Impella 3.5 was placed under fluoroscopic guidance, obtaining the optimal inlet area placement 4 cm below the aortic valve. Shortly after, haemodynamic impairment and haemolysis parameters were noted. Transthoracic echocardiogram (Panel A, see Supplementary data online, Video S1) showed device displacement against the lateral ventricular wall (arrow). Two-dimensional transoesophageal echocardiogram (TEE; Panel B, see Supplementary data online, Video S2) was unable to confirm accurately the device component positions (possible inlet area = star, pigtail not visualized). Three-dimensional (3D) TEE mid-oesophageal long-axis (Panel C, see Supplementary data online, Video S3) and short-axis views (Panel D, see Supplementary data online, Video S4) showed the device outlet area across the aortic valve with the outflow pumped against the right coronary leaflet (arrow head) causing the subsequent haemolysis and haemodynamic impairment. The device was repositioned (Panel E, see Supplementary data online, Video S5) until achieving the output area properly placed (arrow head) in the aortic root. A modified long-axis (Panel F, see Supplementary data online, Video S6) and cranial ‘enface’ view (Panel G, see Supplementary data online, Video S7) showed the device extending into the left ventricle, the relation with the mitral valve, the optimal inlet area placement 4 cm below the aortic valve (star), and the pigtail away from the heart wall (double-star). The 3D TEE is becoming an excellent tool for guidance on interventional procedures, being able to determine the device relations with adjacent structures with a higher spatial accuracy and from non-standard views. LV, left ventricle; RV, right ventricle; LA, left atria; RA, right atria; MV, mitral valve; AV, aortic valve.

Supplementary data are available at European Heart Journal – Cardiovascular Imaging online.

Conflict of interest: none declared.