A new approach to assess myocardial work by non-invasive left ventricular pressure–strain relations in hypertension and dilated cardiomyopathy

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Aims
Non-invasive left ventricular (LV) pressure–strain loop (PSL) provides a novel method of quantifying myocardial work (MW) with potential advantages over conventional global longitudinal strain (GLS) by incorporating measurements of myocardial deformation and LV pressure. We investigated different patterns of LV PSL and global MW index (GWI) in patients with hypertension (HTN) and dilated cardiomyopathy (CMP).

Methods and results
Seventy-four patients underwent transthoracic echocardiography and strain analysis before coronary angiography. Patients were divided into three groups: control, HTN, and CMP. GWI was calculated as the area of the LV PSL as a product of strain/C2 systolic blood pressure. MW efficiency (GWE) is derived from the percentage ratio of constructive work (GCW) to sum of constructive work (GCW) and wasted work (GWW). Influences of HTN and LV function on its relationship with MW were evaluated. GLS and LV ejection fraction were preserved in the HTN group with no difference from controls. GWI was significantly higher in moderate to severe HTN patients (P = 0.004) as a compensatory mechanism to preserve LV contractility and function against an increase in afterload. GWE was preserved in HTN patients due to the proportional increase in GCW and GWW. GLS, GWI, and GWE were significantly reduced in CMP (P < 0.05), with a trend in rightward shift and reduction in the LV PSL.

Conclusion
GWI is a potential new technique that allows better understanding of the relationship between LV remodelling and increased wall stress under different loading conditions.

Keywords
myocardial work • strain • speckle tracking • myocardial function

Introduction
Myocardial deformation imaging using 2D speckle-tracking echocardiography (STE) has allowed advancements in left ventricular (LV) quantification beyond ejection fraction (EF) as a superior prognostic marker of cardiac events. However, one of the main limitations of strain imaging is load dependency, which can affect the diagnostic accuracy of myocardial function evaluation. An increase in afterload has been proven to decrease strain leading to misinterpretation of the true contractile function. Myocardial work (MW) is a new parameter that takes into account deformation as well as afterload through interpretation of strain in relation to dynamic non-invasive LV pressure, potentially offering incremental value to myocardial function assessment.
Suga and Sagawa developed invasively obtained LV pressure–volume loops, providing haemodynamic parameters of contractility, elastance, power, energetics, and efficiency. It has been shown that for any given contractile state of the LV, the pressure–volume area linearly correlates to myocardial oxygen consumption. Invasively measured LV pressure–volume loops derived during coronary angiogram is not without risk to the patient, and therefore, non-invasively derived MW may be of use during routine echocardiographic studies. Recently, Russell et al. demonstrated the validity of non-invasive MW through combining LV strain data with non-invasively estimated LV pressure curves. The area within the LV pressure–strain loop (PSL), represents MW.

Early work suggests LV PSL may provide additional information regarding dysynchronous contraction, segmental work, and myocardial contractility with responders to cardiac resynchronization therapy showing higher global constructive MW. MW has also recently been shown to identify acute coronary occlusion in patients with non-ST-elevation acute coronary syndrome.

This study aimed to: (i) describe the different patterns of LV PSL in patients with hypertension, ischaemic, and non-ischaemic cardiomyopathies and (ii) evaluate the influence of blood pressure, LV function, and LV size on their relationship with MW in these populations. MW (including components of constructive and wasted work) and efficiency were compared with regional and global echocardiographic parameters.

**Methods**

**Study cohort**

This was a single-centre, prospective study recruiting consecutive patients referred for coronary angiography with clinically appropriate indications. The study was approved by the Prince Charles Hospital Human Research and Ethics Committee. Informed consent was obtained from all patients.

Patients with suboptimal image quality for myocardial deformation analysis, valvular heart disease, intracardiac shunts, and cardiac arrhythmias were excluded. The study cohort was divided into three main groups:

1. Controls: no significant coronary artery disease (<50% stenosis) proven on coronary angiography, normal LV size and EF, no other comorbidities, and no regular medications;
2. Patients with a history of hypertension (HTN) with elevated systolic blood pressure (SBP) at the time of the study, normal LV size and EF. HTN patients were subdivided, in accordance with the World Health Organization HTN guidelines into: (i) HTN_1 (SBP ranging from 140 mmHg to 159 mmHg) and (ii) HTN_2 (SBP >160 mmHg);
3. Patients with dilated cardiomyopathy (CMP) (LV diastolic volume >74 mL/m², EF ≤40%), were sub-divided according to Felker et al. guidelines into: (i) non-ischaemic CMP (CMPNILS): no evidence of significant coronary artery stenosis or single-vessel disease with no history of myocardial infarction or revascularization and (ii) ischaemic CMP (CMPILS): coronary artery stenosis (70%) in ≥2 vessels, or history of prior coronary artery bypass grafting or revascularization.

**Echocardiographic analysis**

Comprehensive transthoracic echocardiography was performed immediately prior to coronary angiography by experienced sonographers using a Vivid E95 ultrasound system equipped with a MSS 3.5 mHz transducer (GE Vingmed Ultrasound, Horten, Norway). All recordings and measurements were made according to the American Society of Echocardiography guidelines. Patients were scanned in the left lateral decubitus position with standard 2D images consisting of three cardiac cycles triggered to the QRS complex saved in cine-loop digital format for offline analysis. LV mitral inflow velocities were obtained by pulsed-wave Doppler echocardiography. Septal and lateral mitral annular early myocardial relaxation velocities were obtained using Doppler tissue imaging from the apical four-chamber view for estimates of LV filling pressure. Using 2D imaging, end-systolic wall stress (ESWS) was measured using the end-systolic posterior wall thickness (PWs) and end-systolic LV dimension (LVDs) using the formula according to Wilson et al.:

\[
\text{ESWS} = 0.98 \times \left( \frac{0.334 \times \text{SBP} \times \text{LVDs}}{\text{PWs}} \right) \times (1 + \frac{\text{PWs}}{\text{LVDs}}) - 2
\]

**Global longitudinal strain**

Images from the apical four, two and long-axis views were acquired with a frame rate between 50–80 frames/s (mean 58.4 ± 7.3 frames/s) to assess global longitudinal strain (GLS) by STE. GLS was quantified using semi-automated function imaging (EchoPAC Version 202, GE Vingmed Ultrasound, Norway). Aortic valve closure was identified using the automated function from the apical long-axis view. Automated tracking of myocardial motion was performed with the region of interest adjusted by correcting the endocardial border or width if deemed necessary. GLS was calculated from the weighted average of the peak systolic longitudinal strain of all 17 segments.

**Myocardial work analysis**

MW was calculated using a vendor-specific module through a combination of LV strain and a non-invasively estimated LV pressure curves. Peak systolic LV pressure is assumed to be equal to the peak arterial pressure, which was recorded from the brachial cuff systolic pressure measured immediately prior to the echocardiographic study. The software then constructs a non-invasive LV pressure curve adjusted according to the duration of isovolumic and ejection phases defined by valvular timing events. The area within the PSL provided an index of MW. The following parameters were calculated:

1. Global MW index (GWI): total work within the area of the LV PSL calculated from mitral valve closure to mitral valve opening.
2. Constructive MW: work performed by the LV contributing to LV ejection during systole. Constructive MW is classified as shortening of the myocytes during systole, adding lengthening of the myocytes during isovolumic relaxation.
3. Wasted MW: work performed by the LV that does not contribute to LV ejection. Wasted MW is classified as lengthening of myocytes (rather than shortening) during systole adding shortening during the isovolumic relaxation phase.
4. MW Efficiency: constructive MW/(constructive MW + wasted MW) (these values will not be affected by peak LV pressure).

Figure 1 illustrates how a normal LV PSL begins with an initial rapid rise in LV pressure but minimal change in strain during isovolumic contraction. Once the aortic valve opens, ventricular ejection leads to an increase in GLS (becoming more negative) with myocardial deformation reaching its highest point just as LV pressure begins to decline. Ventricular pressure then falls rapidly with little change in myocardial strain corresponding to isovolumic relaxation. Once LV pressure falls below left atrial pressure in
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**Results**

**Patient characteristics**

Seventy-four patients (mean 67.4 ± 13.6 years; 69% men) fulfilled the inclusion criteria (Table 1). There were no inter-group differences for body surface area, body mass index, or resting heart rate. HTN groups and CMPISC subgroup were significantly older (P < 0.05). SBP was significantly higher (P < 0.05) in both HTN subgroups. All CMPISC patients had >70% stenosis in at least two coronary arteries, three of which had prior coronary artery bypass grafting, and two with previous percutaneous coronary interventions. Brachial cuff SBP was significantly higher (P < 0.05) in total HTN and its subgroups, as well as total CMP and CMPISC compared with invasively measured SBP.

**Echocardiographic analysis**

Patients with pressure-loaded LV (both HTN subgroups) had normal LV dimensions (2D linear dimensions and end-diastolic volume), mildly increased LV wall thickness and LV mass compared with controls, but this did not reach statistical significance (Table 2). ESWS was not significantly increased in HTN patients compared with controls.

Marked LV dilatation and reduction in LVEF were observed in patients with CMP. LV mass was significantly increased (P < 0.05) within both CMP subgroups due to eccentric hypertrophy and LV remodelling, and therefore, ESWS was significantly increased (P < 0.05). Despite a significant reduction in LVEF, LV forward stroke volume remained preserved in both CMP groups (Table 2). Diastolic function parameters revealed significantly reduced (P < 0.05) average septal E' for both CMP subgroups with average E/E' significantly higher (P < 0.05) for the total CMP group and CMPISC subgroup.

**Influences of hypertension on MW**

LVEF was preserved and well compensated with small and non-significant reductions in GLS in the HTN group (Table 2). MW revealed a significant elevation in GWI in patients with HTNGrade2/3 (P < 0.05; 2590 ± 435 mmHg%) and a tendency for GWI to be higher in HTNGrade1 (P = 0.90; 2052 ± 374 mmHg%) compared with controls (1900 ± 165 mmHg%) (Figure 2A). Higher GWI was graphically represented on the bull’s-eye plot in Figure 2B (top panel), displaying predominately red shading in a representative HTN patient compared with a control patient (Figure 2A, top panel), showing uniform green shading (indicating normal GWI) across all 17 segments of the myocardium.

Constructive MW was elevated in HTNGrade1 but did not reach significant levels (P = 0.87; 2361 ± 377 mmHg%) and significantly elevated in HTNGrade2/3 (P = 0.0001; 3057 ± 403 mmHg%) when compared with controls (2184 ± 192 mmHg%) (Figure 2C). Wasted MW was elevated in both HTN subgroups but not statistically significant (Figure 2D). Overall, there was no difference in MW efficiency between controls and HTN (Figure 2B) with uniform, green shading across all 17 segments (Figure 2B, middle panel).

**Influences of cardiomyopathy on MW**

GLS for CMP was significantly lower (P < 0.001) compared with controls (Table 2). Differences in LV MW pattern for CMP patients

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**Figure 1** LV pressure–strain loops showing relationship between timing of cardiac events to change in LV pressure and GLS. AVC, aortic valve closure; AVO, aortic valve opening; MVC, mitral valve closure; MVO, mitral valve opening.

**Figure 2A** Early diastole and the mitral valve opens, the LV rapidly relaxes during diastasis.

**Figure 2B** Angiography

Coronary angiography was performed and analysed by experienced cardiologists, blinded to echocardiographic results using standard techniques. A coronary lesion of >70% in diameter was determined to be significant stenosis. LV end-diastolic pressure was measured by LV gram via a 4- or 5-Fr fluid filled catheter placed into the LV from a femoral or radial approach. LV end-diastolic pressure was recorded just before the injection of the contrast agent and was measured at the nadir of the atrial contraction wave before the onset of the rapid rise in LV systolic pressure.

**Statistical analysis**

All statistical analyses were performed using SPSS statistical software; version 25.0 (SPSS Inc., Chicago, USA). Continuous variables are summarized as mean values ± standard deviation or as percentages. Categorical variables are presented as numbers and percentages. Comparisons between patient groups and subgroups were compared with the control group. Normal distribution was verified by Shapiro–Wilk test. Comparison of the continuous variables among groups was performed by one-way analysis of variance (ANOVA), with Tukey’s post hoc comparisons. Significant differences were determined by the cardiologist repeating measurements from the same images. Intra- and inter-observer variabilities were calculated by intra-class correlation coefficient (ICC) and the standard error of measurement.

**Intra- and inter-observer variability**

Twenty-five patients were randomly selected and remeasured by two observers (experienced cardiac sonographer and cardiologist) blinded to patient clinical data and each other’s results. Intra-observer variability was performed by the experienced cardiac sonographer on off-line data at different points in time. Inter-observer variability was performed by the cardiologist repeating measurements from the same images. Intra- and inter-observer variabilities were calculated by intra-class correlation coefficient (ICC) and the standard error of measurement.
### Table 1  Patient demographics and medications

<table>
<thead>
<tr>
<th></th>
<th>Controls (n = 8)</th>
<th>Hypertension (HTN)</th>
<th>Cardiomyopathy (CMP)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hypertension (HTN)</td>
<td>Cardiomyopathy (CM)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HTN (n = 37)</td>
<td>HTN_Grade1 (n = 24)</td>
<td>HTN_Grade2/3 (n = 13)</td>
</tr>
<tr>
<td>Age (years)</td>
<td>53.5 ± 13.0</td>
<td>71.8 ± 11.4* (P = 0.001)</td>
<td>69.7 ± 12.8* (P = 0.02)</td>
</tr>
<tr>
<td>Heart rate (b.p.m.)</td>
<td>64 ± 13</td>
<td>65 ± 13 (P = 0.97)</td>
<td>64 ± 13 (P = 1.0)</td>
</tr>
<tr>
<td>Blood pressure (mmHg)</td>
<td>126 ± 9</td>
<td>158 ± 15* (P = 0.0001)</td>
<td>149 ± 6* (P = 0.006)</td>
</tr>
<tr>
<td>Medications</td>
<td></td>
<td></td>
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<tr>
<td>Beta blocker</td>
<td>0 (0%)</td>
<td>11 (30%)</td>
<td>9 (38%)</td>
</tr>
<tr>
<td>Calcium channel blocker</td>
<td>0 (0%)</td>
<td>14 (38%)</td>
<td>11 (46%)</td>
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<td>ACE inhibitor</td>
<td>0 (0%)</td>
<td>18 (49%)</td>
<td>13 (54%)</td>
</tr>
<tr>
<td>Angiotensin II receptor blocker</td>
<td>0 (0%)</td>
<td>13 (35%)</td>
<td>7 (29%)</td>
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<tr>
<td>Statin</td>
<td>0 (0%)</td>
<td>20 (54%)</td>
<td>12 (50%)</td>
</tr>
<tr>
<td>Nitrates</td>
<td>0 (0%)</td>
<td>8 (22%)</td>
<td>5 (21%)</td>
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</tbody>
</table>

*P < 0.05, significantly different from controls.
**P < 0.05, significantly different from cuff SBP.

LVEDP, left ventricular end-diastolic pressure.
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### Table 2: Conventional echocardiography parameters

<table>
<thead>
<tr>
<th></th>
<th>Controls (n = 8)</th>
<th>Hypertension (HTN)</th>
<th>Cardiomyopathy (CMP)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total HTN (n = 37)</td>
<td>HTN_Grade1 (n = 24)</td>
<td>HTN_Grade2/3 (n = 13)</td>
</tr>
<tr>
<td>LVDd (mm)</td>
<td>47.1 ± 4.0</td>
<td>48.0 ± 5.0 (P = 0.95)</td>
<td>48.4 ± 5.0 (P = 0.99)</td>
</tr>
<tr>
<td>LVDs (mm)</td>
<td>31.2 ± 3.1</td>
<td>31.4 ± 4.0 (P = 0.99)</td>
<td>32.3 ± 3.8 (P = 0.99)</td>
</tr>
<tr>
<td>IVSd (mm)</td>
<td>9.0 ± 1.2</td>
<td>10.9 ± 1.7* (P = 0.02)</td>
<td>10.8 ± 1.2 (P = 0.11)</td>
</tr>
<tr>
<td>PWd (mm)</td>
<td>9.2 ± 1.2</td>
<td>10.1 ± 1.5 (P = 0.28)</td>
<td>10.0 ± 1.4 (P = 0.66)</td>
</tr>
<tr>
<td>LV mass (g)</td>
<td>147.7 ± 37.2</td>
<td>185.8 ± 55.7 (P = 0.26)</td>
<td>184.9 ± 60.0 (P = 0.58)</td>
</tr>
<tr>
<td>LV mass indexed (g/m²)</td>
<td>76.8 ± 10.2</td>
<td>92.3 ± 23.2 (P = 0.32)</td>
<td>90.5 ± 19.3 (P = 0.73)</td>
</tr>
<tr>
<td>ESWS (× 10⁵ dyn/cm²)</td>
<td>69.4 ± 15.6</td>
<td>79.1 ± 16.3 (P = 0.79)</td>
<td>77.7 ± 16.8 (P = 0.98)</td>
</tr>
<tr>
<td>Biplane EDV (mL)</td>
<td>87.5 ± 13.9</td>
<td>102.3 ± 30.3 (P = 0.63)</td>
<td>107.3 ± 32.4 (P = 0.08)</td>
</tr>
<tr>
<td>EDV indexed (mL/m²)</td>
<td>45.7 ± 4.1</td>
<td>50.5 ± 11.6 (P = 0.83)</td>
<td>52.0 ± 12.6 (P = 0.95)</td>
</tr>
<tr>
<td>Biplane ESV (mL)</td>
<td>34.1 ± 7.1</td>
<td>39.2 ± 12.5 (P = 0.93)</td>
<td>42.2 ± 13.3 (P = 0.98)</td>
</tr>
<tr>
<td>Biplane SV (mL)</td>
<td>53.4 ± 8.2</td>
<td>63.1 ± 19.3 (P = 0.29)</td>
<td>65.1 ± 20.5 (P = 0.42)</td>
</tr>
<tr>
<td>Biplane EF (%)</td>
<td>61.2 ± 4.4</td>
<td>61.7 ± 4.2 (P = 0.97)</td>
<td>60.7 ± 4.1 (P = 0.99)</td>
</tr>
<tr>
<td>GLS (%)</td>
<td>19.0 ± 2.5</td>
<td>17.5 ± 3.2 (P = 0.52)</td>
<td>16.8 ± 3.4 (P = 0.65)</td>
</tr>
<tr>
<td>E' average (cm/s)</td>
<td>8.8 ± 2.3</td>
<td>7.5 ± 1.7 (P = 0.12)</td>
<td>7.4 ± 1.8 (P = 0.30)</td>
</tr>
<tr>
<td>E/E’ average</td>
<td>7.9 ± 1.9</td>
<td>10.3 ± 4.8 (P = 0.71)</td>
<td>10.6 ± 4.7 (P = 0.88)</td>
</tr>
</tbody>
</table>

*P < 0.05, significantly different from controls.

E', mitral annular early diastolic velocity; E/E', ratio between early mitral inflow velocity and mitral annular early diastolic velocity; EDV, end-diastolic volume; ESV, end-systolic volume; ESWS, end-systolic wall stress; GLS, global longitudinal strain; IVSd, diastolic interventricular septal thickness; LVDd, left ventricular diameter diastole; LVDS, left ventricular diameter systole; PWd, diastolic posterior wall thickness; SV, stroke volume.
Figure 2  Graph of mean and standard error of the mean across all groups. (A) GWI; (B) GWE; (C) GCW; (D) GWW. *P < 0.05, significantly different from controls. GCW, global constructive work; GWE, global myocardial work efficiency; GWI, global work index; GWW, global wasted work.

Figure 3 (Top panel) Seventeen-segment bull’s-eye representation of MW index (GWI) showing areas of negative work in blue, normal in green, and red indicating areas of high MW; (Middle panel) 17-segment bull’s-eye representation of MW efficiency (GWE) showing areas of high efficiency coded in green and those with the least efficiency coded in red; (Bottom panel) LV PSL. Examples of patients within: (A) control group; (B) HTN Grade 2/3; (C) CM P-ISC; (D) CM IBC.
is evident by markedly reduced GWI for CMPN-ISC (P < 0.001; 1078 ± 506 mmHg%) and further reductions for CMPISC (P < 0.001; 916 ± 452 mmHg%) when compared with controls (1900 ± 165 mmHg%) (Figure 2A). Reduced GWI is graphically displayed on the bull’s-eye plot for both CMPN-ISC and CMPISC (Figure 3C and D, top panel, respectively). The blue colour-coding visualized within the GWI bull’s-eye plot indicates increased areas of negative work with significantly increased wasted MW for CMPN-ISC (P < 0.001; 226 ± 128 mmHg%) and a non-significant increase in wasted MW for CMPISC (P = 0.49; 138 ± 76 mmHg%) compared with controls (74 ± 24 mmHg%) (Figure 2B). There was a concomitant reduction in constructive MW for both CMP subgroups (P < 0.05; 1460 ± 550 and 1145 ± 587 mmHg%, CMPN-ISC and CMPISC, respectively) compared with controls (2184 ± 192 mmHg%) (Figure 2C). Therefore, the ratio of MW efficiency is also significantly reduced (P < 0.05; 83.2 ± 9.0 and 83.2 ± 11.3%, CMPN-ISC and CMPISC, respectively, compared with controls (95.9 ± 1.6%) (Figure 2D).

Table 3  Interclass correlation coefficient for intra- and inter-observer variability for MW parameters and GLS

<table>
<thead>
<tr>
<th></th>
<th>Intra-observer variability</th>
<th>Inter-observer variability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ICC  95% CI</td>
<td>SEM  95% CI</td>
</tr>
<tr>
<td>Myocardial work index (mmHg%)</td>
<td>0.953 0.863–0.981</td>
<td>215.9</td>
</tr>
<tr>
<td>GLS (%)</td>
<td>0.949 0.793–0.982</td>
<td>1.5</td>
</tr>
<tr>
<td>Global myocardial work efficiency (%)</td>
<td>0.988 0.973–0.995</td>
<td>1.4</td>
</tr>
<tr>
<td>Global constructive work (mmHg%)</td>
<td>0.967 0.889–0.987</td>
<td>212.0</td>
</tr>
<tr>
<td>Global wasted work (mmHg%)</td>
<td>0.941 0.867–0.974</td>
<td>32.8</td>
</tr>
<tr>
<td>GLS (%)</td>
<td>0.949 0.793–0.982</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Discussion

This study describes the patterns of non-invasive MW derived from LV PSL in normal subjects (CON), patients with varying degrees of HTN, and those with CMPN-ISC and CMPISC. The study cohort permitted evaluation of the influence of afterload and intrinsic contractile dysfunction, on parameters of myocardial deformation and work. The primary findings of this study were: (i) Despite normal GLS in HTN, GWI was significantly higher with no changes in MW efficiency when compared with control and (ii) Co-existent with low GLS, CMPN-ISC and CMPISC have significant reductions in GWI and MW efficiency due to a combination of decreased constructive and increased wasted MW.

MW assessment has traditionally been dependent on invasive pressure measurements, limiting its feasibility in adaptation into routine clinical practice. Non-invasive estimation of MW has shown a strong correlation with values obtained invasively and was developed by pooling invasive pressure measurements across a range of...
pathologies and normalizing pressure curves. Individual patient curves are estimated by measuring valvular timing events by echocardiography and then normalized by stretching or compressing the curve to equal durations of isovolumic contraction, ejection and isovolumic relaxation. The amplitude of the curve is derived using peripheral blood pressure. Exclusion of aortic stenosis is important as the peripheral blood pressure will not be an accurate reflection of LV pressure.

**Influences of hypertension on MW**

Increased GWI in patients with HTN is a similar finding to conventional invasive LV pressure–volume loop tracings acquired by cardiac angiography. Stroke work, calculated by integrating the area of the LV pressure–volume loop, was higher in the pressure overloaded LV (102 ± 14 g/m² vs. 41 ± 12 g/m², P < 0.05). When the LV pumps against high arterial pressure, there is a short-term reduction of LV stroke volume, compensated by shifting the pump function of the LV to a higher energy level, reflected as higher levels of GWI within this study cohort, not detectable by GLS alone. On the other hand, GWI does take into account the increased afterload in HTN. Borlaug et al. also reported higher LV end-systolic stiffness in 719 patients with HTN.

LV end-systolic stiffness is an index of myocardial contractility reflecting the ability of the LV to pump against a given pressure with higher levels associated with enhanced myocardial contractility. This phenomenon of increased GWI in uncontrolled HTN patients to match arterial afterload allows preservation of EF and endocardial motion, reflected in the preservation of GLS within this patient cohort. However, chronically increased cardiac loading eventually leads to increased LV stiffness and concentric remodelling and eventually LV failure. Interestingly, MW efficiency is preserved with no changes in early HTN with preserved GLS because MW efficiency is derived indirectly from the ratio of constructive and wasted MW. There was almost a proportional increase in both constructive and wasted work so that MW efficiency remained constant. The increase in wasted MW may also be related to the increase wall stress in the myocardium against a higher afterload.

**Influences of ischaemic and non-ischaemic CMP on MW**

Despite severe LV dilatation and reduced EF in CMP NISC and CMP ISC, cardiac output can be maintained at nearly normal levels due to a preserved stroke volume. In contrast, reduced GWI revealed a significantly impaired contractile performance of the cardiomyocytes within CMP patients, demonstrating the inadequacies of EF measurements. The findings from this study are also reflected in previously reported invasive LV pressure–volume loops determined from cardiac magnetic resonance imaging which demonstrated reduced stroke work. Importantly, both CMP subgroups displayed significantly (P < 0.05) higher levels of wasted MW (LV work not contributing to LV ejection), reducing the MW efficiency of the dilated LV. Increased wasted MW has been found in dysynchronous ventricles with significant reductions along with increases in EF following cardiac resynchronization therapy. Non-uniformity in wall motion reduces the mechanical efficiency of ventricular ejection.

LV remodelling characterized by ventricular dilatation and contractile dysfunction are important determinants of adverse prognosis in CMP patients. GLS is a superior marker of LV function compared with EF for prediction of events and prognosis. The prognostic significance of reduced GWI and MW efficiency in patients with CMP remains unknown and warrants further investigation.

**Effects of cuff SBP**

A limitation of LV PSL estimation is the inaccuracy of brachial cuff pressure as a surrogate for central aortic pressure and LV systolic pressure as evidenced by the statistically significant difference in cuff pressures compared with invasive pressure in this study. This inaccuracy became more pronounced in HTN patients, with the largest difference in patients with grade 2/3 HTN. This is in agreement with previous work published by Hubert et al. who also showed differences in maximum systolic values of measured and estimated pressures with brachial cuff pressure being imprecise and becoming more evident with higher arterial pressures. Despite these discrepancies, Hubert et al. conclude that estimation of LV MW is accurate due to the integration of time and less pressure difference from aortic valve opening to closure.

**End-systolic wall stress**

ESWS measures the maximal load that can be sustained by the myocardial fibres at end-systole and is dependent on myocardial mass and cavity dilatation. In agreement with Alter et al. patients with increased afterload showed slightly elevated but no significant difference in ESWS compared with controls, whereas patients with CMP demonstrated significantly increased ESWS. Myocardial hypertrophy caused by sustained increases in afterload compensates for increased wall stress and significant increases in GWI. LV dilatation of in addition to increased myocardial mass observed in CMP patients results in the observed significantly elevated ESWS and reduction in GWI.

**Limitations**

Our study was only able to describe various patterns of LV PSL and MW relationships with HTN and CMP. We demonstrated that the pressure–strain estimates of MW are sensitive to different afterload conditions in comparison to conventional GLS, which is regarded as load dependent, and also influenced by intrinsic contractile dysfunction. This early work suggests that MW may potentially be useful in the assessment of myocardial deformation mechanics, but our study did not prove that it is superior to GLS. Larger scale studies are needed for further evaluation of this new parameter to establish its clinical utility and prognostic implications.

Arterial systolic pressure measured with a cuff and sphygmomanometer in the brachial artery can be imprecise as systolic pressure varies throughout the arterial tree. Central systolic pressure can be lower than the brachial systolic pressure due to pressure augmentation and in patients with brachial vascular disease.

Arrhythmias, with significant beat-to-beat variability, inhibit accurate and reliable assessment of STE with the viability of MW estimation questionable in such patients. Patients with inadequate image quality limit the accuracy of STE, leading to suboptimal MW assessment.
A new approach to assess myocardial work

Summary

Analysis of LV function through non-invasive LV PSL and calculation of MW allows global and regional ventricular mechanics to be analysed through the relationship between myocardial contractility and LV pressure. Evaluation using GLS does not inherently incorporate afterload assessment. Non-invasive MW estimation may allow a better understanding of the relationship between LV remodelling and increased wall stress under different loading conditions.

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