European Heart Journal – Cardiovascular Imaging (2013) **14**, 805–811
doi:10.1093/ehjci/jes295

# Global and regional longitudinal strain assessed by two-dimensional speckle tracking echocardiography identifies early myocardial dysfunction and transmural extent of myocardial scar in patients with acute ST elevation myocardial infarction and relatively preserved LV function

**S. Cimino[1], E. Canali[1], V. Petronilli[1], F. Cicogna[1], L. De Luca[1], M. Francone[2], G. Sardella[1], C. Iacoboni[1], and L. Agati[1]***

[1]Department of Cardiology, 'Sapienza' University of Rome, Roma, Italy; and [2]Department of Radiology, 'Sapienza' University of Rome, Roma, Italy

*Received 3 September 2012; accepted after revision 21 November 2012; online publish-ahead-of-print 20 December 2012*

**Aims** Global and regional longitudinal strain (GLS–RLS) assessed by two-dimensional speckle tracking echocardiography (2D-STE) are considered reliable indexes of left-ventricular (LV) function and myocardial viability in chronic ischaemic patients when compared with delayed-enhanced cardiac magnetic resonance (DE-CMR). In the present study, we tested whether GLS and RLS could also identify early myocardial dysfunction and transmural extent of myocardial scar in patients with acute ST elevation myocardial infarction (STEMI) and relatively preserved LV function.

**Methods and results** Twenty STEMI patients with LVEF $\geq$40%, treated with PPCI within 6 h from symptoms onset, underwent DE-CMR and 2D-echocardiography for 2D-STE analysis $6 \pm 2$ days after STEMI. Wall motion score index (WMSI) and LV ejection fraction (LVEF) were calculated by both methods. Infarct size and transmural extent of necrosis were assessed by CMR. GLS and RLS were obtained by 2D-STE. Mean GLS of the study population was $-14 \pm 3.3$, showing a significant correlation with both LVEF and WMSI, by CMR ($r = -0.86$, $P = 0.001$, and $r = 0.80$, $P = 0.001$, respectively) and time-to-PCI ($r = 0.66$, $P = 0.038$). A weaker correlation was found between GLS and LVEF and WMSI assessed by 2D-echo ($r = -0.65$, $P = 0.001$, and $r = 0.53$, $P = 0.013$, respectively). RLS was significantly lower in DE-segments when compared with normal myocardium ($P < 0.0001$). A cut-off value of RLS of $-12.3\%$ by receiver-operating characteristic (ROC) curves identified DE-segments (sensitivity 82%, specificity 78%), whereas a cut-off value of $-11.5\%$ identified transmural extent of DE (sensitivity 75%, specificity 78%).

**Conclusion** Our findings indicate that RLS and GLS evaluation provides an accurate assessment of global myocardial function and of the presence of segments with transmural extent of necrosis, with several potential clinical implications.

**Keywords** ST elevated myocardial infarction (STEMI) • Cardiac magnetic resonance (CMR) • Two-dimensional speckle tracking echocardiography (2D-STE) • Global longitudinal strain (GLS) • Regional longitudinal strain (RLS)

* Corresponding author. Fax: +39 06 49 97 9060, Email: luciano.agati@uniroma1.it

# Introduction

Accurate diagnosis, characterization, and quantification of myocardial infarction (MI) are essential to assess the impact of therapy and to aid in predicting prognosis of patients with ischaemic heart disease. After MI, the alteration of global and regional LV function and the presence of myocardial viability depend on both infarct size (IS) and transmural extension of necrosis.[1–3] Infarct size is a major determinant of mortality,[4–6] and transmural infarcts are associated with a worse prognosis and more adverse cardiac events.[7] Therefore, accurate assessment of IS and the identification of segments with transmural extent of necrosis plays a central role in the prediction of prognosis.

Cardiac magnetic resonance (CMR) is a non-invasive and highly reproducible imaging technique able to assess LV damage after MI. Cardiac magnetic resonance imaging allows accurate evaluation of LV regional and global function evaluating left-ventricular volumes, ejection fraction (LVEF), and wall motion score index (WMSI) with cine imaging. Delayed contrast-enhanced CMR (DE-CMR) identifies tissue damage due to increased contrast agent retention within infarcted areas, caused by cell-membrane rupture and increased interstitial space.[8,9] DE-CMR imaging is the gold standard for quantification of infarct extent and transmurality.[10] This technique also represents a good early predictor of infarct severity, because of its ability to identify reduced perfusion areas that ultimately results in cell necrosis, membrane rupture, reduced contractility, remodelling, and heart failure.[11] However, the routine use of CMR in the acute phase of MI is limited. Further, patients' factors can sometimes preclude the usefulness of the technique: claustrophobia, presence of cranial aneurysm clips, ocular metallic shards, and pacemakers. Moreover, the need for breath-holding to remove respiratory motion artefact can also present problems for some patients with severe cardiac or respiratory disease.

Two-dimensional speckle tracking echocardiography (2D-STE) is a B-mode images-based technique that can quantify regional myocardial deformation independently by insonation angle and thus simultaneously assess systolic long-axis strain and short-axis shortening.[12] The accuracy of 2D-STE was confirmed using sonomicrometry and MRI tagging as reference methods.[13] Global longitudinal strain (GLS) is considered an effective parameter for quantifying left-ventricular function[14,15] more sensitive than LVEF assessed by 2D echocardiography and their role in large MI has been previously reported.[16] We hypothesized that longitudinal strain representing the sub-endocardial zones of the myocardial wall segments that are less perfused and more vulnerable to conditions of ischaemia, could provide additional information regarding LV function when compared with LVEF and WMSI in STEMI patients with mild LV dysfunction. Adequate functional evaluation in this kind of patients should be more difficult than in patients with an evident myocardial dysfunction and history of ischaemic myocardial diseases.

Aim of this study was to compare 2D-STE and CMR in LV regional and global function assessment and in particular to relate regional longitudinal strain (RLS) as assessed by 2D-STE with transmural extent of DE segments identified by CMR in patients with acute MI and relatively preserved LV function.

# Methods

## Study population

A population of 20 patients (mean age 57 $\pm$ 10), admitted to the coronary care unit of our hospital with diagnosis of ST elevation MI (STEMI) and timely reperfused within 6 h from symptom onset was enrolled. All patients underwent DE-CMR and 2D-STE 3 $\pm$ 2 days after the acute event. Inclusion criteria were: (i) typical chest pain lasting more than 30 min and unresolved by nitroglycerine; (ii) ST segment elevation $>$0.1 mV in at least two contiguous leads in the initial electrocardiogram (ECG); (iii) elevated markers of myocardial necrosis; (iv) treatment with PPCI within 6 h from symptoms' onset. Exclusion criteria were: (i) LV ejection fraction $<$40%; (ii) previous MI; (iii) previous PCI or coronary artery bypass intervention; (iv) cardiogenic shock; (v) contraindications to perform CMR; (vi) presence of arrhythmias of precluding adequate STE and CMR analysis.

## Echocardiography

Complete two-dimensional and Doppler echocardiograms were performed using a standard commercial ultrasound machine (Philips IE33®). Routine B-mode grey scale images were acquired in the apical four- chamber, apical two chambers, 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. A 16-segment model was used to subdivide the LV for subsequent analysis.[17] The digital loops were stored and analysed by the vendor-independent 2D CPA (Cardiac Performance Analysis)-Tomtec® software for frame-by-frame movement of stable patterns of speckles. 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. Both global and regional longitudinal strains were obtained: global strain values were calculated by averaging all segmental peak systolic strain values in a 16 segment model. Only segments available for a correct ST analysis were compared with the corresponding segments analysed by CMR. Longitudinal strain was also calculated in 20 normal subjects to obtain the reference normal range of our software.

## Cardiac magnetic resonance

As previously described,[18] DE-CMR was performed using a 1.5 T scanner (Avanto-Siemens, Erlangen-Germany). Infarcted tissue was identified using DE images. Images were acquired in short-axis, four-chamber and two-chamber views, and during breath hold, in base conditions and 15 min after intravenous administration of a Gadolinium-based contrast agent (Gadolinium-BOPTA, Multihance, Bracco, Milan, Italy; 0.1 mmol/kg body weight at 2 mL/s). All CMR studies were analysed off-line by using a dedicated workstation (Siemens Argus, Erlangen, Germany). Left-ventricular ejection fraction, LV end-systolic and end-diastolic BSA-adjusted volumes, and LV mass were obtained. Infarcted tissue was defined as an area of gadolinium hyperenhancement in a sub-endocardial or transmural pattern and in the territory of a coronary artery. Infarct size was calculated and expressed in percentage of LV mass. The same 16-segment model used for 2D-STE analysis was applied. Regional contrast enhancement was scored with a scheme based on the extent of hyperenhanced tissue in each segment (transmural infarction = 100% of hyperenhancement extent, non-transmural infarction = 75, 50, or 25% of hyperenhancement extent). WMSI was calculated as the ratio of the sum of wall motion over total segments.

## Statistical analysis

All data were analysed with standard statistical software (PASW statistics, Version 18.0, Chicago, IL). All categorical variables are expressed as percentages and all continuous variables as mean ± standard deviation (SD). Correlations between GLS and LVEF, WMSI and time-to-PCI were performed by Spearman linear regression analysis. Reproducibility was assessed in 10 randomly selected patients and expressed as the absolute difference between two paired measurements divided by their average. Receiver-operating-characteristic (ROC) curves were constructed to evaluate the ability of 2D-STE to distinguish non-enhanced from enhanced segments and to identify transmural-infarcted segments. Areas under curves (AUCs) were also measured to determine cut-off values with maximum sensitivity and specificity. Two-tailed *t*-test for unpaired data and Mann–Whitney test were used to assess differences between groups. A two-side *P*-value of $<0.05$ was considered statistically significant.

# Results

## Patient characteristics

Of the 20 patients enrolled in this study, 18 were male (90%). Clinical characteristics at presentation are shown in *Table 1*. DE-CMR and 2D standard echocardiography data are listed in *Tables 2–4*. Angiographic characteristics of the study population are listed in *Table 5*.

## Global function analysis

Intra- and inter-observer variability for GLS analysis were 2.5 ± 1.2% and 4.7 ± 1.5%, respectively. Mean GLS in the control group was −20 ± 1.1, whereas in the study population it was −14 ± 3.3 ($P = 0.001$). Spearman linear regression analysis showed that GLS significantly correlate with both LVEF ($r = -0.86$, $P = 0.001$), and WMSI assessed by CMR ($r = 0.80$; $P = 0.001$) and with time-to-PCI ($r = 0.66$; $P = 0.038$) (*Figures 1–3*).

**Table 1 Characteristic of the study population at presentation**

| Male sex, % | 90% |
|---|---|
| Age, years | 57 ± 10 |
| Hypertension, % | 53 |
| Smoke, % | 59 |
| Diabetes, % | 5.9 |
| Dyslipidaemia, % | 78 |
| Family history of CAD, % | 35 |
| Killip Class I | 100 |
| Time-to-PCI, min | 157 ± 80 |
| TroponinT peak, UI/L | 11 ± 19 |
| CK-MB peak, UI/L | 151 ± 193 |
| SBP at admission, mmHg | 131 ± 43 |
| DPB at admission, mmHg | 85 ± 10 |
| HR at admission, bpm | 69 ± 26 |

CAD, coronary artery disease; SBP, systolic blood pressure; DBP, diastolic blood pressure; HR, heart rate.

**Table 2 Cardiac magnetic resonance data**

| | |
|---|---|
| LVEF, % | 50 ± 10 |
| LVEDVi | 66 ± 11 |
| LVESVi | 15 ± 12 |
| AAR, g | 27 ± 21 |
| MS, % | 10 ± 9 |
| IS, % | 11 ± 9 |
| WMSI | 1.47 ± 0.3 |

LVEF, left-ventricular ejection fraction; LVEDVi, left-ventricular end-diastolic volume BSA-adjusted; LVESVi, left-ventricular end-systolic volume BSA adjusted; AAR, area at risk; MS, myocardial salvage; IS, infarct size; WMSI, wall motion score index.

**Table 3 Cardiac magnetic resonance: degree of transmurality**

| TME, % | Frequency | Percent |
|---|---|---|
| 00 | 190 | 76 |
| 25 | 6 | 2.4 |
| 50 | 5 | 2 |
| 75 | 10 | 4 |
| 100 | 39 | 15.6 |
| Total | 250 | |

TME, transmural extent.

**Table 4 Echocardiographic parameters**

| | |
|---|---|
| LVEF, % | 48 ± 4.5 |
| WMSI | 1.48 ± 0.2 |
| GLS, % | −14 ± 3.3 |
| Left atrium, mL | 68 ± 22 |
| E wave | 81 ± 3.9 |
| A wave | 72 ± 21 |
| E/A | 1.2 ± 0.49 |
| DT, ms | 196 ± 26 |
| e' | 8.2 ± 2.8 |
| E/e' | 9 ± 1.6 |

LVEF, left-ventricular ejection fraction; WMSI, wall motion score index; GLS, global longitudinal strain; DT, deceleration time.

A significant but weaker correlation between both LVEF ($r = -0.65$, $P = 0.001$), and WMSI assessed by 2D echo ($r = 0.53$, $P = 0.013$) was found. GLS was also calculated according to 2D-echo WMSI values. GLS was −15.2 ± 2.7 in the subset of patients with normal WMSI (=1) and −13.9 ± 3.9 in the subset with abnormal WMSI (>1), $P = 0.201$. Finally, GLS showed significant linear correlations with CK-MB peak ($r = 0.84$, $P = 0.004$) and Troponin-T peak ($r = 0.86$, $P = 0.003$).

**Table 5 Angiographic data**

| | |
|---|---|
| Single-vessel disease, % | 50 |
| Multi-vessel disease, % | 50 |
| Culprit lesion LAD, % | 65 |
| Culprit lesion RCA, % | 29 |
| Culprit lesion LCx, % | 6 |
| Stent implanted, number | 1.6 ± 0.9 |
| GP IIbIIIa at PCI, % | 99 |
| Aspirin at PCI, % | 11 |
| Clopidogrel at PCI, % | 60 |
| Prasugrel at PCI, % | 25 |
| TIMI pre-PCI | 0.5 ± 0.9 |
| TIMI post-PCI | 3 |

LAD, left anterior descending; RCA, right coronary artery; LCx, left circumflex artery; PCI, percutaneous coronary intervention.

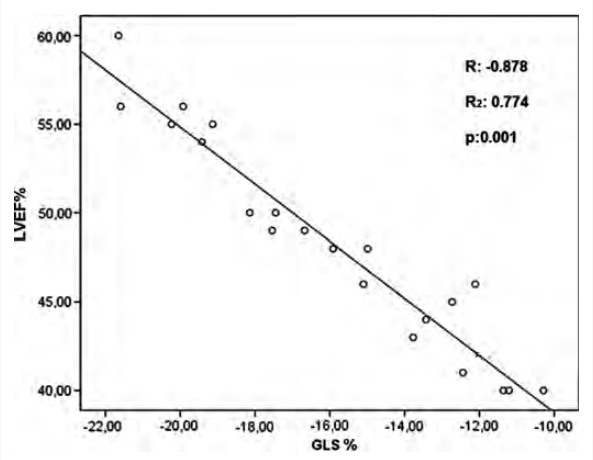



**Figure 1** Linear correlation between global longitudinal strain and LV ejection fraction (CMR). GLS, global longitudinal strain; LVEF, left-ventricular ejection fraction; CMR, cardiac magnetic resonance.

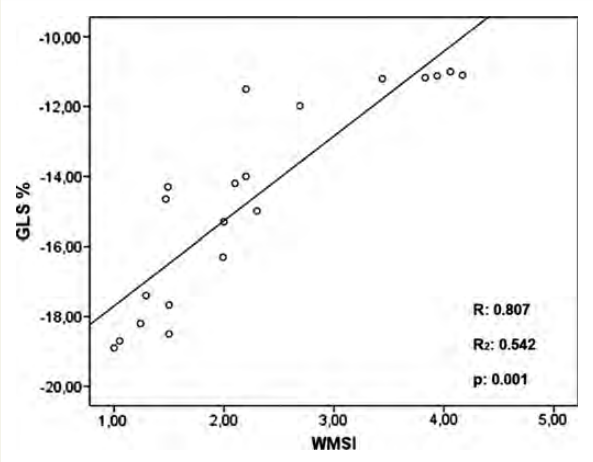



**Figure 2** Linear correlation between global longitudinal strain and WMSI (CMR). GLS, global longitudinal strain; WMSI, wall motion score index; CMR, cardiac magnetic resonance.

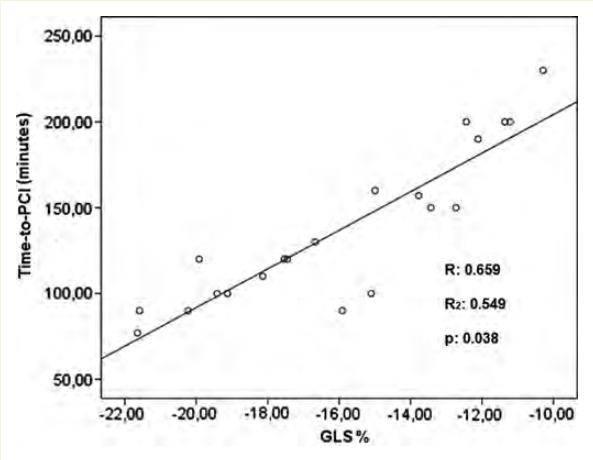



**Figure 3** Linear correlation between global longitudinal strain and time-to-PCI. GLS, global longitudinal strain.

## Regional function analysis

A total of 250 out of 320 segments were analysed in this study by both 2D-STE and CMR. The remaining 70 segments were inadequate for a correct 2D-STE analysis. Transmural extent of necrosis was detected by LGE-CMR in 39 (16%).

Absolute values of RLS were significantly lower in DE myocardial segments when compared with normal myocardium (−15 ± 7.5 vs. −11 ± 5.7, with $P < 0.0001$) and transmural-infarcted segments had a significant lower absolute value of RLS when compared with non-transmural ones (−10 ± 7.5 vs. −14 ± 8.3, $P = 0.016$) (*Figure 4*a and b). However, difference between normal and non-transmural segments was not significant (−15 ± 7.5 vs. −14 ± 8.3, ns).

A cut-off value of RLS of −12% identified enhanced segments with a sensitivity of 82% and a specificity of 78%. A cut-off value of −11% identified transmural MI with a sensitivity of 75% and a specificity of 78% (*Figure 5*a and b).

# Discussion

The present paper demonstrates for the first time that in patients with mild LV dysfunction after acute MI, the analysis of longitudinal strain curves by 2D-STE imaging may add significant information as for global and regional LV function assessed by traditional 2D-echocardiography. Even in patients with a relatively preserved LV function after acute MI, longitudinal strain analysis is a sensitive method to detect slight global LV function impairment and it is also able to identify the presence of areas of DE and its transmural extent.

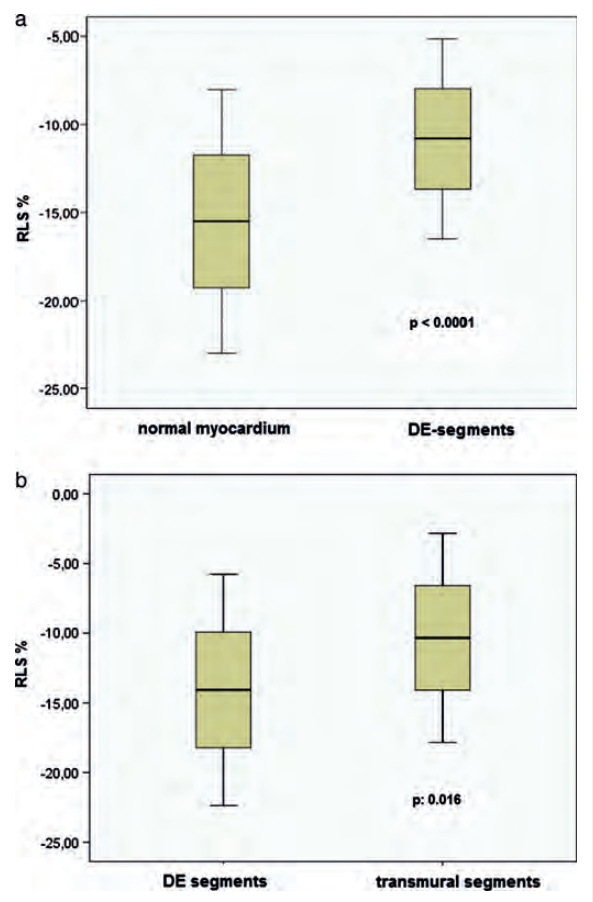



**Figure 4** (a) Regional longitudinal strain: normal myocardium vs. DE segments. (b) Regional longitudinal strain: non-transmural segments vs. transmural ones. RLS, regional longitudinal strain; DE, delayed enhancement.

## GLS and the evaluation of global LV function after MI

A significant correlation between GLS and both LVEF and WMSI evaluated by CMR, used as reference method, was found. These correlations were higher than that observed between GLS and LVEF and WMSI evaluated by 2D echo. In particular, GLS was reduced also in the subset of patients with normal 2D-echo WMSI underlying the additional value of this parameter in global LV function assessment. Previous studies already established that GLS has several advantages in the evaluation of LV function when compared with LVEF by echocardiography.[19,20] However, in these papers, the study population included also patients with large IS and markedly impairment of global LV function. Our study population included only patients with small IS and preserved or mildly reduced global and regional LV function. Even in this subset of patients, GLS analysis is a sensitive parameter of global LV impairment.

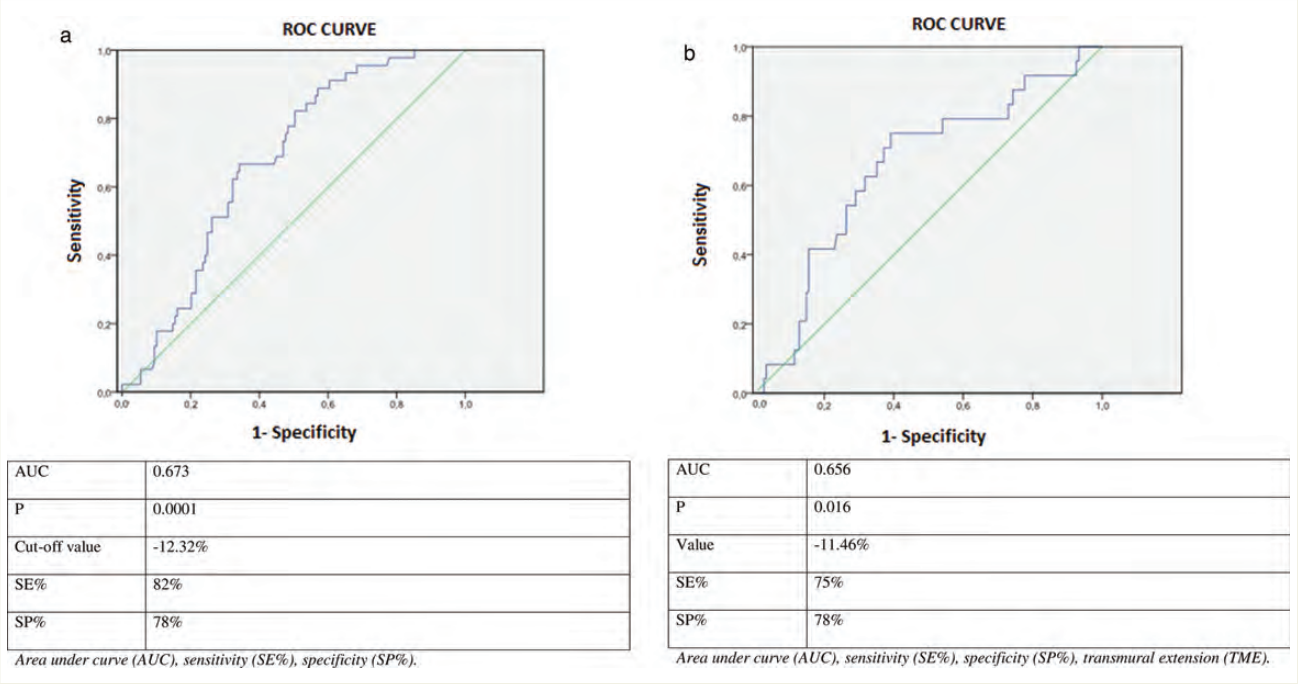
## Regional longitudinal strain and delayed enhancement

The present study demonstrates that RLS is lower in segments with areas of DE evaluated by CMR. In particular, RLS is significantly lower in transmural segments. Thus, the evaluation of RLS allows a reliable identification of segments with transmural extent of myocardial necrosis. Identification of transmural infarction is clinically important because of its prognostic implications. There is a close relationship between different degrees of ischaemic injury, mortality, and morbility.[21] It is well known that when transmural extent of DE is >50% of the entire segment, the likelihood of increased contractility after revascularization[7] is strongly reduced. CMR is the gold standard method identifying myocardial scar. IS measurement can also be achieved by biochemical[22] and electrocardiographic methods[23,24] or by imaging modalities, such as scintigraphy[25] and 2D echocardiography.[26–28] Echocardiographic techniques are the most easily available in the acute phase after MI, so, an ultrasound-based index which can also identify transmural myocardial segment should be considered an important clinical tool.

Previous[29–31] studies proved the reliability of longitudinal strain in identifying ischaemic areas. In particular, RLS closely related with other signs of MI, such as wall thickening, angiographic findings, and ECG signs of ischaemia. In our paper, we compared RLS directly with CMR, the gold standard evaluation for assessing IS. Our data clearly showed that RLS analysis is a reliable and sensitive tool to detect small areas of MI, also able to identify their transmurality.

The relationship between RLS and the presence of myocardial scar evaluated by CMR has been already reported in previous papers.[32,33] A recent study by Sengupta *et al.*,[32] performed on a heterogeneous population of patients with myocardial scar, demonstrated the reduction of RLS independently by delayed enhancement location (sub-endocardial, sub-epicardial, mid-myocardial, and transmural). Jonathan *et al.*[33] showed that, in chronic ischaemic patients, enhanced myocardial segments had a reduction in longitudinal strain ($-13 \pm 5.6$ vs. $-17 \pm 5.4$, $P < 0.0001$) compared with normal myocardium. In these papers, the authors described also radial and circumferential strain as predictors of IS. In our study, we took into account only the longitudinal component of myocardial strain, because, as previously described, radial and circumferential strain measurements resulted to be not so reliable.[34] They are highly subjected to the image quality and to the suitability of parameter setting for image acquisition. When validated against CMR, transmural strain and circumferential strain by 2D-STE have also been reported to have only a weak correlation.[35,36]

Bax *et al.*,[37] previously demonstrated the association between GLS and RLS measured by 2D-STE with the global and regional transmural extent of myocardial scar as measured by CMR. A cut-off value of −4.5% for regional strain discriminated between segments with viable myocardium and those with transmural scar tissue with a sensitivity of 81% and specificity of 81%. Cut-off values identified in our study are quite different. A possible explanation of this discrepancy could be that this mentioned study was performed on a population of chronic ischaemic patients with markedly reduced LVEF ($28 \pm 8$%), identifying irreversible ischaemic damage in those who have yet a clear evidence of functional alteration and known history of ischaemic myocardial diseases. Softwares used for strain analysis were also different, thus further explaining the different cut-off values found.




| | |
|---|---|
| AUC | 0.673 |
| P | 0.0001 |
| Cut-off value | -12.32% |
| SE% | 82% |
| SP% | 78% |

*Area under curve (AUC), sensitivity (SE%), specificity (SP%).*

| | |
|---|---|
| AUC | 0.656 |
| P | 0.016 |
| Value | -11.46% |
| SE% | 75% |
| SP% | 78% |

*Area under curve (AUC), sensitivity (SE%), specificity (SP%), transmural extension (TME).*

**Figure 5** (a) ROC curve: delayed enhancement segments vs. non-enhanced ones. (b) ROC curve: TME 100% segments vs. non-transmural segments. AUC, area under curve; SE%, sensitivity; SP%, specificity. RLS, regional longitudinal strain; DE, delayed enhancement; TME, transmural extension.

## GLS and time-to-PCI

An important result which confirmed the relationship of this parameter with the presence of ischaemic myocardium is the significant linear correlation between GLS and time-to-PCI. It is well known that time to reperfusion determines the extent of reversible and irreversible myocardial injury: a shorter time-to-reperfusion is associated with smaller IS and microvascular obstruction and larger salvaged myocardium[38]; moreover, delays in recanalizing the occluded artery in patients with STEMI influence IS extent[39,40] with a strong impact on prognosis.[41] The present study confirms that a longer time-to-reperfusion is associated with lower values of longitudinal strain, suggesting a reduction of myocardial systolic shortening in prolonged conditions of ischaemia. This association defines a possible role of this new parameter in predicting prognosis of patients after acute MI, but this result has to be confirmed with further studies.

## Study limitations

Our study, in line with the literature, confirms that GLS is a useful diagnostic tool for assessing LV function, but it's prognostic value and the impact on major cardiac adverse events has to be confirmed with further studies based on follow-up data.

Another limitation of the study is that it is based on a small population. Our results have to be confirmed on a larger sample.

Moreover, it has to be considered that myocardial systolic strain is a load-dependent parameter and that it should be interpreted with care if there are changes of loading conditions. We examined our patients in stable clinical conditions (Killip Class I), verifying the clinical usefulness of the method, but it's value in unstable patients has to be established.

Finally, although strain analysis is able to clearly differentiate between normal and transmurally enhancing segments, the differentiation between normal and non-transmural ones is less evident.

# Conclusions

Global longitudinal strain assessed by 2D-STE is an accurate index of global LV function, while regional strain is a sensitive method to identify also small areas of DE and to identify transmural-infarcted segments in patients with acute MI and preserved or mildly reduced systolic function.

Our findings indicate that this method provides a rapid, easy, and non-invasive assessment of global myocardial function and of the presence of segments with transmural extent of necrosis, with several potential clinical implications.

**Conflict of interest:** none declared.

## References

1. Choi KM, Kim RJ, Gubernikoff G, Vargas JD, Parker M, Judd RM. Transmural extent of acute myocardial infarction predicts long-term improvement in contractile function. *Circulation* 2001;**104**:1101–7.
2. Christian TF, Schwartz RS, Gibbons RJ. Determinants of infarct size in reperfusion therapy for acute myocardial infarction. *Circulation* 1992;**86**:81–90.
3. Pfeffer MA, Braunwald E. Ventricular remodeling after myocardial infarction. Experimental observations and clinical implications. *Circulation* 1990;**81**:1161–72.
4. Pfeffer MA, Pfeffer JM. Ventricular enlargement and reduced survival after myocardial infarction. *Circulation* 1987;**75**:IV93–97.

5. Pislaru C, Bruce CJ, Anagnostopoulos PC, Allen JL, Seward JB, Pellikka PA *et al.* Ultrasound strain imaging of altered myocardial stiffness: stunned versus infarcted reperfused myocardium. *Circulation* 2004;**109**:2905–10.
6. Reffelmann T, Hale SL, Li G, Kloner RA. Relationship between no reflow and infarct size as influenced by the duration of ischemia and reperfusion. *Am J Physiol Heart Circ Physiol* 2002;**282**:H766–H72.
7. Kim RJ, Wu E, Rafael A, Chen EL, Parker MA, Simonetti O *et al.* The use of contrast enhanced magnetic resonance imaging to identify reversible myocardial dysfunction. *N Eng J Med* 2000;**343**:1445–53.
8. Wu KC, Lima JA. Noninvasive imaging of myocardial viability: current techniques and future developments. *Circ Res* 2003;**93**:1146–58.
9. Plein S, Younger JF, Sparrow P, Ridgway JP, Ball SG, Greenwood JP. Cardiovascular magnetic resonance of scar and ischemia burden early after acute ST elevation and non-ST elevation myocardial infarction. *J Cardiovasc Magn Reson* 2008;**10**:47.
10. Ingkanisorn WP, Rhoads KL, Aletras AH, Kellman P, Arai AE. Gadolinium delayed enhancement cardiovascular magnetic resonance correlates with clinical measures of myocardial infarction. *J Am Coll Card* 2004;**43**:2253–9.
11. Gerber BL, Raman SV, Nayak K, Epstein FH, Ferreira P, Axel L *et al.* Myocardial first-pass perfusion cardiovascular magnetic resonance: history, theory, and current state of the art. *J Cardiovasc Magn Reson* 2008;**10**:18.
12. Blessberger H, Binder T. Two dimensional speckle tracking echocardiography: basic principles. *Heart* 2010;**96**:716–22.
13. Amundsen BH, Helle-Valle T, Edvardsen T, Torp H, Crosby J, Lyseggen H *et al.* Noninvasive myocardial strain measurement by speckle tracking echocardiography validation against sonomicrometry and tagged magnetic resonance imaging. *J Am Coll Card* 2006;**47**:789–93.
14. Urheim S, Edvardsen T, Torp H, Angelsen B, Smiseth OA. Myocardial strain by Doppler echocardiography. Validation of a new method to quantify regional myocardial function. *Circulation* 2000;**102**:1158–64.
15. Brown JBS, Jenkins CMS, Marwick TH. Use of myocardial strain to assess global left ventricular function: a comparison with cardiac magnetic resonance and 3-dimensional echocardiography. *Am Heart J* 2009;**157**:102.e1–e5.
16. Sjoli B, Orn S, Grenne B, Vartdal T, Smiseth OA, Edvardsen T *et al.* Comparison of left ventricular ejection fraction and left ventricular global strain as determinants of infarct size in patients with acute myocardial infarction. *J Am Soc Echocardiogr* 2009;**22**:1232–8.
17. Armstrong WF, Pellikka PA, Ryan T, Crouse L, Zohgbi WA. Stress echocardiography recommendations for performance and interpretation for stress echocardiography. Stress echocardiography task force of the nomenclature and Standard Committee of the American Society of echocardiography. *J Am Soc Echocardiogr* 1998;**11**:97–104.
18. Masci PG, Francone M, Desmet W, Ganame J, Todiere G, Donato R *et al.* Right ventricular ischemic injury in patients with acute ST-segment elevation myocardial infarction. Characterization with cardiovascular magnetic resonance. *Circulation* 2010;**122**:1405–12.
19. Reisner SA, Lysyansky P, Agmon Y, Mutlak D, Lessick J, Friedman Z. Global longitudinal strain: a novel index of left ventricular systolic function. *J Am Soc Echocardiogr* 2004;**17**:630–3.
20. Mistry N, Beitnes JO, Halvorsen S, Abdelnoor M, Hoffmann P, Kjeldsen SE *et al.* Assessment of left ventricular function in ST-elevation myocardial infarction by global longitudinal strain: a comparison with ejection fraction, infarct size, and wall motion score index measured by non-invasive imaging modalities. *Eur J Echocardiogr* 2011;**12**:678–83.
21. Krone R, Friedman E, Thanavaro S, Miller JP, Kleiger R, Oliver GC. Long term prognosis after first Q-wave (transmural) or non Q-wave (non transmural) myocardial infarction: analysis of 593 patients. *Am J Card* 1983;**52**:234–9.
22. Herlitz J, Hjalmarson A, Waldenstrom J. Relationship between different enzymatic estimations of the infarct size. *Acta Cardiol* 1985;**40**:217–28.
23. Wagner GS, Freye CJ, Palmeri ST, Roark SF, Stack NC, Ideker RE *et al.* Evaluation of a QRS scoring system for estimating myocardial infarct size. Specificity and observer agreement. *Circulation* 1982;**65**:342–7.
24. Juergens CP, Fernades C, Hasche ET, Meikle S, Bautovich G, Currie CA *et al.* Electrocardiographic measurement of infarct size after thrombolytic therapy. *J Am Coll Cardiol* 1996;**27**:617–24.
25. Sharpe DN, Botvinick EH, Shames DM, Norman A, Chatterjee K, Parmley WW. The clinical estimation of acute myocardial infarct size with 99mTechnetium pyrophosphate scintigraphy. *Circulation* 1978;**57**:307–13.
26. Møller JE, Hillis GS, Oh JK, Reeder GS, Gersh BJ, Pellikka PA. Wall motion score index and ejection fraction for risk stratification after acute myocardial infarction. *Am Heart J* 2006;**151**:419–25.
27. Kan G, Visser CA, Koolen JJ, Dunning AJ. Short and long term predictive value of admission wall motion score in acute myocardial infarction. A cross sectional echocardiographic study of 345 patients. *Heart* 1986;**56**:422–7.
28. Penco M, Romano S, Agati L, Dagianti A, Vitarelli A, Fedele F *et al.* Influence of reperfusion induced by thrombolytic treatment on natural history of left ventricular regional wall motion abnormality in acute myocardial infarction. *Am J Card* 1983;**71**:1015–20.
29. Gotte MJ, van Rossum AC, Twisk JWR, Kuijer JPA, Marcus JT, Visser CA. Quantification of regional contractile function after infarction: strain analysis superior to wall thickening analysis in discriminating infarct from remote myocardium. *J Am Coll Cardiol* 2001;**37**:808–17.
30. Jamal F, Kukulski T, Sutherland GR, Weidermann F, D'hooge J, Bijnens B *et al.* Can changes in systolic longitudinal deformation quantify regional myocardial function after an acute infarction? An ultrasonic strain rate and strain study. *J Am Soc Echocardiogr* 2002;**15**:723–30.
31. Nishikage T, Takeuchi M, Nakai H, Otsuji Y, Lang RM. Possible link between strain ST-T change on the electrocardiogram and subendocardial dysfunction assessed by two-dimensional speckle-tracking echocardiography. *Eur J Echocardiogr* 2010;**11**:451–9.
32. Kansal MM, Panse PM, Abe H, Caracciolo G, Wilansky S, Tajik J *et al.* Relationship of contrast-enhanced magnetic resonance imaging-derived intramural scar distribution and speckle tracking echocardiography-derived left ventricular two-dimensional strains. *Eur J Echocardiogr* 2012;**13**:152–8.
33. Chan J, Hanekom L, Wong C, Leano R, Goo-Yeong C, Marwick TH. Differantion of subendocardial an transmural infarction using two dimensional strain rate imaging to assess short-axis and long- axis myocardial function. *J Am Coll Cardiol* 2006;**48**:2026–33.
34. Manovel A, Dawson D, Smith B, Nihoyannopoulos P. Assessment of left ventricular function by different speckle-tracking software. *Eur J Echocardiogr* 2010;**11**:417–42.
35. Cho GY, Chan J, Leano R, Strudwick M, Marwick TH. Comparison of two dimensional speckle and tissue velocity based strain and validation with harmonic phase magnetic resonance imaging. *Am J Cardiol* 2006;**97**:1661–6.
36. Becker M, Hoffmann R, Kuhl HP, Grawe H, Katoh M, Kramann R *et al.* Analysis of myocardial deformation based on ultrasonic pixel tracking to determine transmurality on chronic myocardial infarction. *Eur Heart J* 2006;**27**:2560–6.
37. Roes SD, Mollema SA, Lamb HJ, Van der Wall EE, de Roos A, Bax JJ. Validation of echocardiographic two-dimensional speckle tracking longitudinal strain imaging for viability assessment in patients with chronic ischemic left ventricular dysfunction and comparison with contrast-enhanced magnetic resonance imaging. *Am J Cardiol* 2009;**104**:312–7.
38. Francone M, Bucciarelli-Ducci C, Carbone I, Canali E, Scardala R, Calabrese F *et al.* Impact of primary coronary angioplasty delay on myocardial salvage, infarct size and microvascular damage in patients with ST-segment elevation myocardial infarction. *J Am Coll Card* 2009;**54**:2145–53.
39. Bogaert J, Kalanzi M, Rademakers FE, Dymarkowski S, Jansses S. Determinants and impact of microvascular obstruction in successfully riperfused ST-segment myocardial infarction. Assessment by magnetic resonance imaging. *Eur Radiol* 2007;**17**:2572–80.
40. Brodie BR, Webb J, Cox DA, Qureshi M, Kalynych A, Turco M *et al.* Impact of time-to-treatment on myocardial reperfusion and infarct size with primary percutaneous coronary intervention for acute myocardial infarction (from the EMERALD trial). *Am J Cardiol* 2007;**99**:1680–6.
41. De Luca G, Suryapranata H, Ottervenger JP, Antmann E. Time delay to treatment and mortality in primary angioplasty for acute myocardial infarction: every minute of delay counts. *Circulation* 2004;**109**:1223–5.