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Evaluation of myocardial viability in patients with acute myocardial infarction

Layer-specific analysis of 2-dimensional speckle tracking echocardiography

Kun Liu, MD[a,b], Yan Wang, MD[c], Qiongyu Hao, MD[d], Gonghao Li, MD[b], Peng Chen, MD[e], Dongye Li, MD, PhD[a,*]

Abstract

Background: The value of layer-specific two-dimensional speckle tracking echocardiography (LS2D-STE) for evaluating viable myocardium (VM) in patients with acute myocardial infarction (AMI) was unclear, this study provides new insights into it and to make a comparison with dualisotope simultaneous acquisition single photon emission computed tomography (DISA-SPECT).

Methods: Forty hospitalized patients with AMI and left ventricular systolic dysfunction (left ventricular ejection fraction <50%) underwent LS2D-STE and DISA-SPECT before percutaneous coronary intervention (PCI). The longitudinal, circumferential, and radial peak systolic strains and the peak systolic strain rates of 3 myocardiallayers (endocardium, mid-myocardium, and epicardium), as well as the total wall thickness, were determined by LS2D-STE. Routine echocardiography was followedup at 1, 3, 6 months after PCI, with the improvement of the wall motion as the goldenstandard for evaluating VM.

Results: The sensitivity, specificity and accuracy of DISA-SPECT for evaluating VM were 82.1%, 74.3%, and 79.3%, respectively. Among the layer-specific parameters, only endocardial (endo-) longitudinal strain (LS) and endo- longitudinal strain rate (LSr) were used as independent parameters for evaluating VM ($P < .05$), and the sensitivity, specificity and accuracy of endo-LS and endo-LSr in evaluation of VM were 77.1%, 65.4%, and 72.9% vs 72.9%, 65.4%, and 69.7%. Endo-LS and endo-LSr were superior to total wall thickness LS and LSr (AUC endo-LS 0.767 vs total-LS 0.669; endo-LSr 0.743 vs total-LSr 0.682). The parallel test and the serial test of combination of endo-LS and endo-LSr showed similar sensitivity, specificity and accuracy to DISA-SPECT ($P > .05$).

Conclusion: The endo-LS and endo-LSr analysis of LS2D-STE can evaluate the VM well, and its sensitivity, specificity and accuracy in detection of VM are similar to those of DISA-SPECT, resulting in LS2D-STE being a good option for the assessment of VM.

Abbreviations: 3D-STE = 3-dimensional speckle tracking echocardiography, AMI = acute myocardial infarction, CS = circumferential peak systolic strain, CSr = circumferential peak systolic strain rate, DISA-SPECT = dualisotope simultaneous acquisition single photon emission computed tomography, LS = longitudinal peak systolic strain, LS2D-STE = layer-specific 2-dimensional speckle tracking echocardiography, LSr = longitudinal peak systolic strain rate, LVEF = left ventricular ejection fraction, PCI = percutaneous coronary intervention, RS = radial peak systolic strain, RSr = radial peak systolic strain rate, VM = viable myocardium.

Keywords: acute myocardial infarction, layer-specific, 2-dimensional speckle tracking echocardiography, viable myocardium

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KL and YW Equal contributors.

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All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent was obtained from all individual participants included in the study.

The authors declare that there is no conflict of interest.

[a] *Institute of Cardiovascular Disease, Xuzhou Medical University, Xuzhou 221002, Jiangsu Province,* [b] *Department of Cardiology, the Affiliated Lianyungang Hospital of Xuzhou Medical University,* [c] *Department of Echocardiography, the Affiliated Lianyungang Hospital of Xuzhou Medical University, China,* [d] *Department of Cell Biology, New York University School of Medicine, USA,* [e] *Department of Nuclear Medicine, the Affiliated Lianyungang Hospital of Xuzhou Medical University, Lianyungang 222002, Jiangsu Province, China.*

[*] *Correspondence: Dongye Li, Institute of Cardiovascular Disease, Xuzhou Medical University, 84 West Huaihai Road, Xuzhou 221002, Jiangsu Province, China (e-mail: dongyeli_lk@outlook.com).*

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1. Introduction

The mortality of patients with acute myocardial infarction (AMI) decreased significantly after percutaneous coronary intervention (PCI) treatment.[1] Evaluation of viable myocardium (VM) is important for angioplasty in patients with AMI.[2] VM can be evaluated by magnetic resonance imaging (MRI), single photon emission computed tomography (SPECT), positron emission tomography (PET), F-18 fluorodeoxyglucose (18F-FDG), tissue Doppler imaging (TDI) and dobutamine stress echocardiography (DSE).[3–5] PET is the most reliable method to diagnose VM.[6] Some studies have shown that dualisotope simultaneous acquisition single photon emission computed tomography (DISA-SPECT) could assess VM in place of PET, with sensitivity and specificity similar to PET.[7] However, it is difficult for DISA-SPECT to be widely used due to high cost, technical difficulty and radiation pollution.

Speckle tracking echocardiography (STE) is a new method for detecting VM in patients with AMI,[8] which overcomes the dependencies of angle and space, and measures the global strain and strain rate of the left ventricle to assess VM.[9,10] However, the left ventricular (LV) wall is divided into 3 layers, including the endocardial (endo-), mid-myocardial (mid-) and epicardial (epi-) layers, and previous studies investigated the left ventricle as a whole. The purposes of this study were to explore the value of layer-specific 2-dimensional speckle tracking echocardiography (LS2D-STE) for assessing VM in patients with AMI and to make a comparison with DISA-SPECT.

2. Materials and methods

2.1. Study population

The study selected 40 hospitalized patients with AMI who had not undergone primary PCI (29 males, average age 58 years, age range from 48 to 74 years) from February 2016 to July 2017. The selection of patients was based on the ACC/AHA 2009 definition

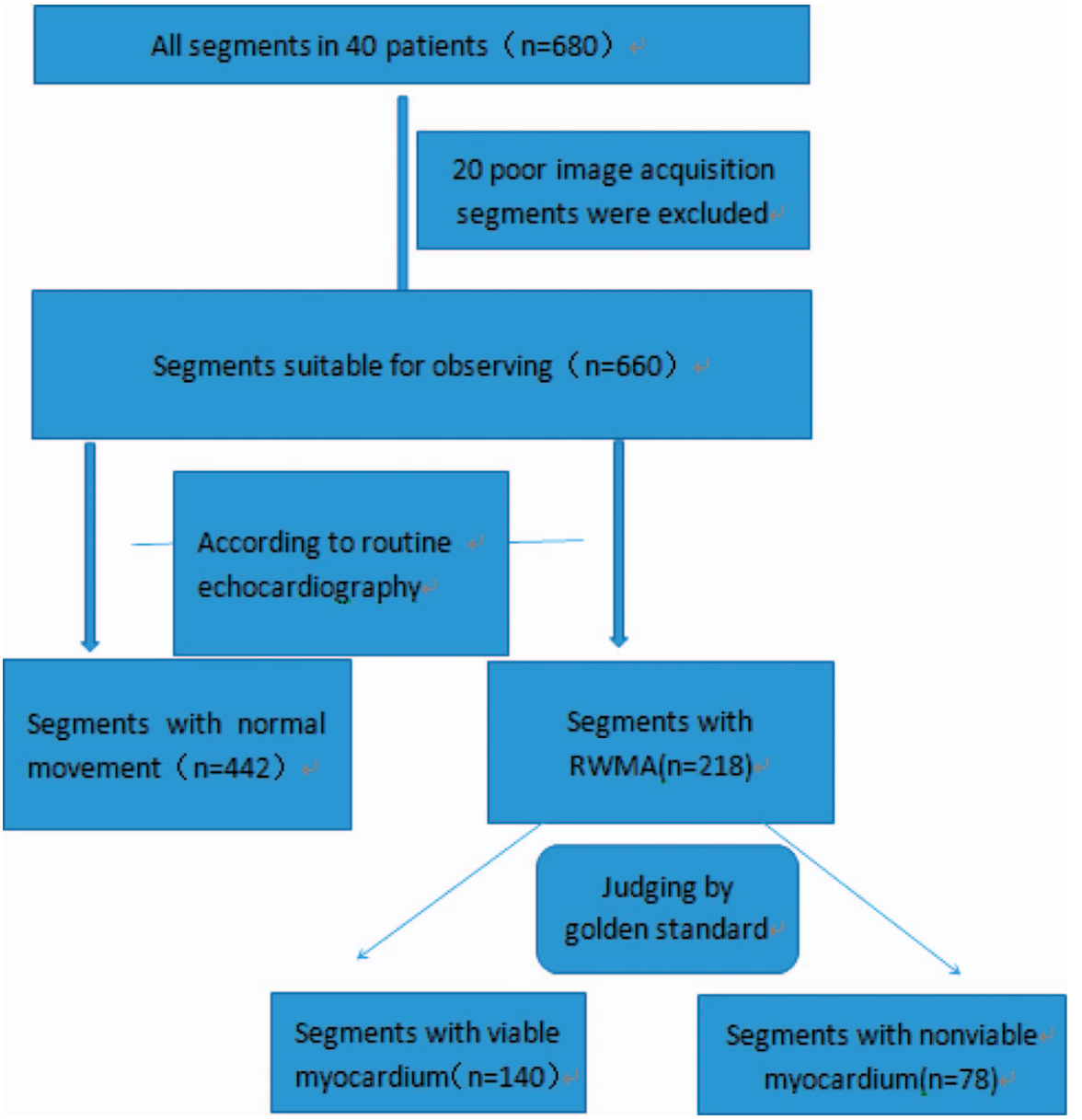

Figure 1. The flow chart of this study.

criteria for acute ST-segment elevation myocardial infarction,[11] the onset time over 24 h, sinus rhythm, and LVEF < 50%. Exclusion criteria: previous AMI history, cardiogenic shock, PCI history, severe arrhythmia, cardiomyopathy, valvular heart disease and congenital heart disease, as well as history of severe obstructive pulmonary disease. All patients were informed of the content of the study and signed the consent before admission. The study was approved by the Ethics Committee of the Affiliated Lianyungang Hospital of Xuzhou Medical University (lygyy 201610).

2.2. Instruments and methods

2.2.1. Echocardiography and wall motion assessment. Within 24 h after admission, conventional transthoracic echocardiography and LS2D-STE were performed bedside. Beta-blockers, calcium antagonists and nitrate drugs were deactivated for at least 12 h before LS2D-STE was completed. The 12-lead electrocardiogram and blood pressure of patients were recorded during the examination. The color Doppler ultrasound diagnostic apparatus (Siemens SC2000, Germany) and S4–1 probe were applied using the American heart association 17-segment divided method.[12] The segments with regional wall motion abnormalities (RWMA) were obtained by conventional echocardiography, and LVEF was measured by the Simpson method. The 2-dimensional images of LV long-axis section and basal section, middle section and apical section of LV short-axis section were collected for 3 cardiac cycles, and gray-scale images were obtained at a frame rate of 50 to 70 frames/s using harmonic (1/3 MHz) B-mode imaging. Two experienced sonographers blinded to the clinical data of patients analyzed the wall motions, with the wall motion thickening rate and the endocardial motion used as the wall motion score.[13] In the 17 LV segments, the wall motion was recorded as: 1, normal; 2, hypokinesia; 3, akinesia; and 4, dyskinesia. The number and score of segments with RWMA were calculated.

2.2.2. LS2D-STE. The 3 consecutive cardiac cycles were acquired during a breath hold, and 3 standard apical long-axis (4-chamber, 2-chamber, and 3-chamber) views, as well as basal, mid, and apical short-axis views were obtained. The Q-Lab workstation was used for offline analysis (software 7.0 Siemens Germany). Getting appropriate myocardial thickness, along with the mitral annulus and the LV apex, we tracked the LV endocardium and got the epicardium at the same time. The boundary of sections, if not satisfactory, were adjusted manually. The software automatically divided the heart muscle into endocardium, mid-myocardium and epicardium, and also automatically gave the speckle tracking results. The longitudinal peak systolic strain (LS), longitudinal peak systolic strain rate (LSr), circumferential peak systolic strain (CS), circumferential peak systolic strain rate (CSr), radial peak systolic strain (RS) and radial peak systolic strain rate (RSr) were determined for 3 layers and for total wall thickness in 17 segments during the 3 cardiac cycles (Fig. 2).

2.2.3. Echocardiography follow-up. Routine transthoracic echocardiography was followed up at 1, 3, 6 months after PCI, and the changes of LV wall motion were observed, the

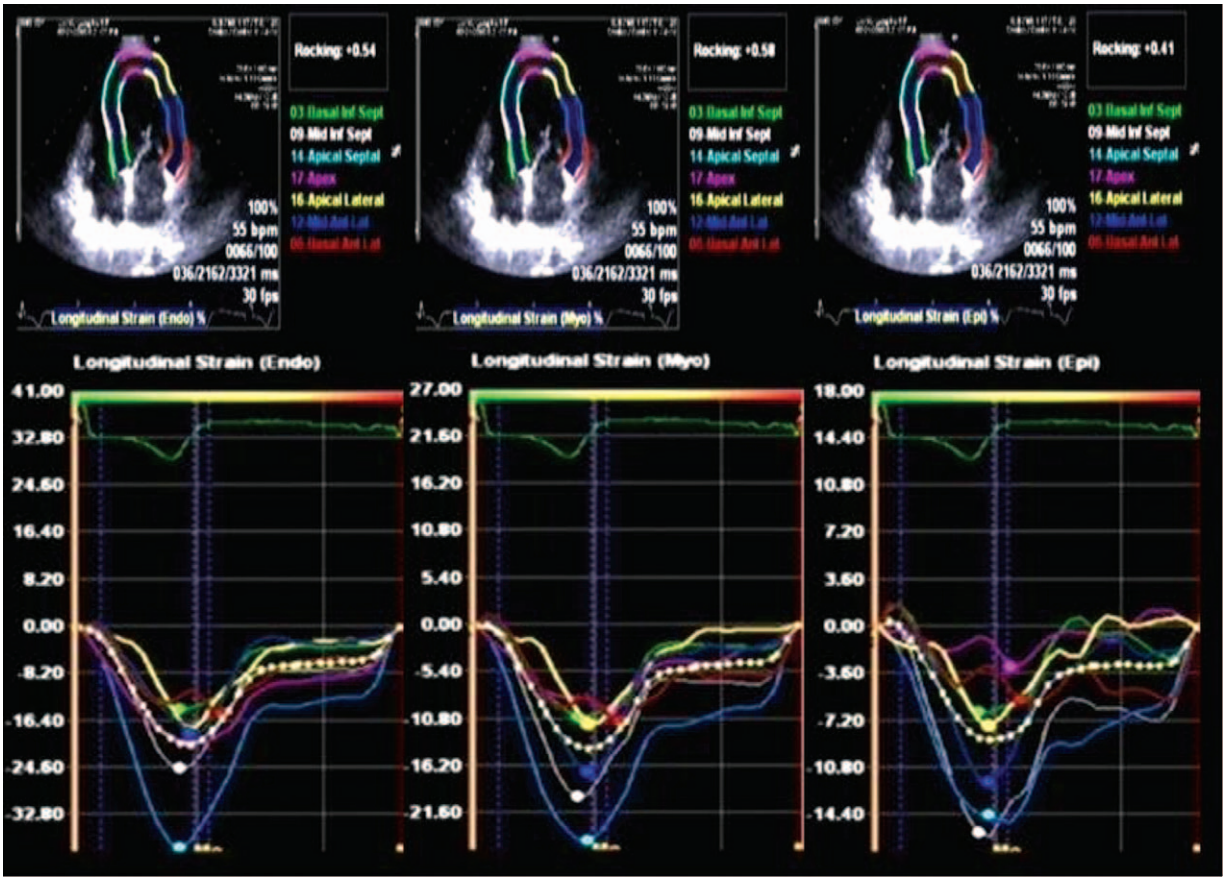

Figure 2. Measurement of myocardial endo-, mid- and epi- longitudinal peak systolic strain using LS2D-STE in left ventricular apical 4-chamber.

golden standard for evaluating VM being that the movement of LV segments improved at least 1 scale after PCI. If the wall motion turned from dyskinesia to akinesia, it was not considered as VM. This standard was considered as the golden diagnostic criterion for VM.[14]

2.2.4. DISA-SPECT. DISA-SPECT was performed 3 days after the completion of LS2D-STE, using the SPECT/CT machine (GE Infinia VC Hawkeye, USA). The patients were injected with ^{99m}Tc- MIBI 740 MBq in the resting state, after 20 min they ate fat meals, and after 45 min, the blood glucose were measured with the automatic glucose meters. If the blood glucose were between 7.7 and 8.8 mmol/l, the intravenous injections of ^{18}F-FDG 296–370mbq were then done at 60 min, and the DISA images were obtained at 120 min (Fig. 3). When they were less than 7.7 mmol/l, the patients were asked to take 25 to 75g glucose

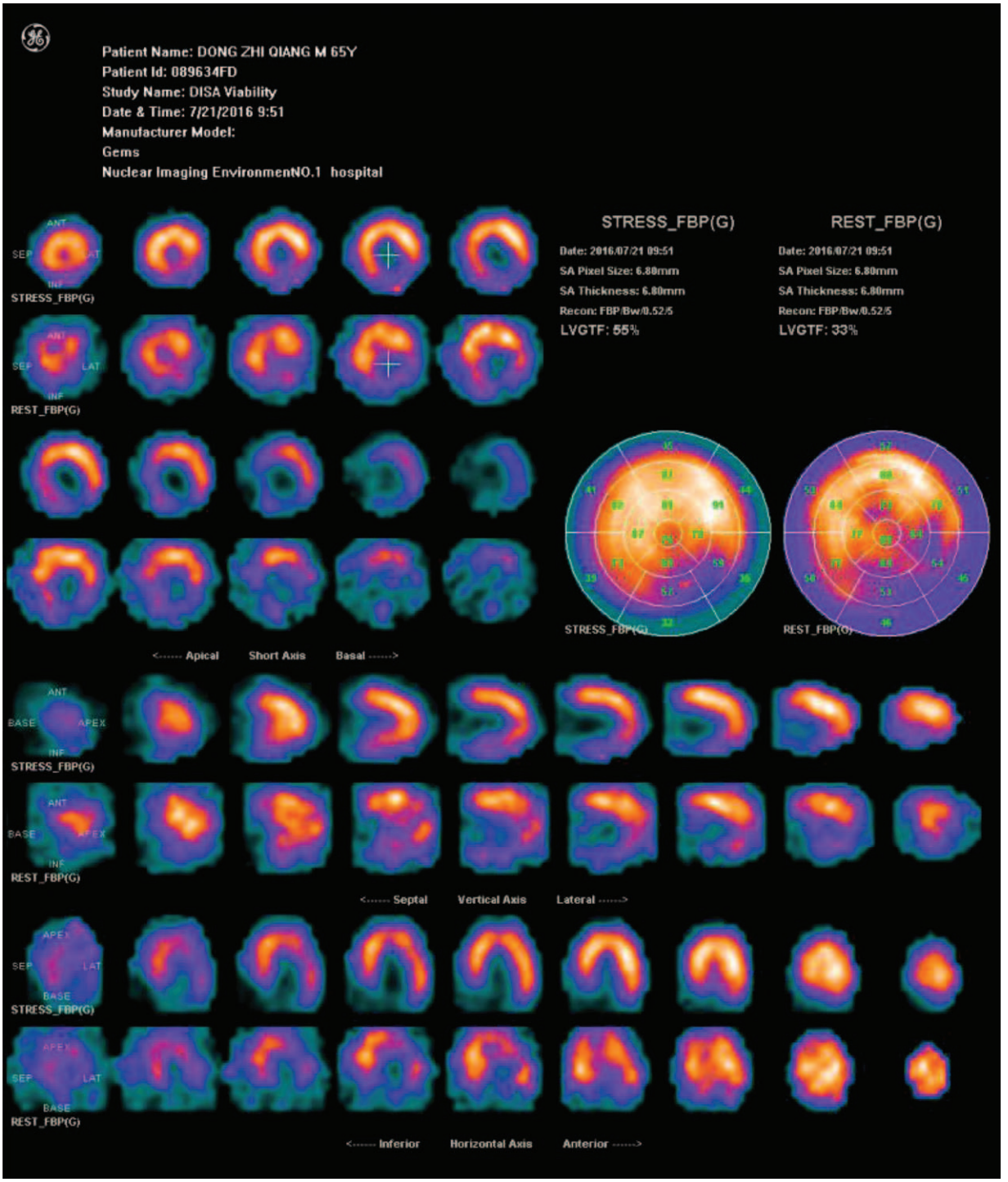

Figure 3. Left ventricular inferior wall and posterolateral wall perfusion sparse or defect, suggest myocardial infarction, and glucose metabolism in most of the above infarct area is low.

solution orally. Suppose they were greater than 8.8 mmol/l or the patients were complicated with diabetes mellitus (DM), the subcutaneous injections of insulin 5 to 20u were done for the patients, and the blood glucose were monitored until they reached the standard (7.7–8.8 mmol/l).

Two nuclear medicine doctors without knowing the results of echocardiography analyzed the images. The myocardial tomography images were divided into 17 LV segments,[15] by semi-quantitative assessment of myocardial blood flow and metabolism: normal (without any fixed or reduced reversibility radioactive anomalies or defect) = score 0, sparse = score 1, significantly sparse = score 2, and obviously defective = score 3. The standard of detecting VM was as follows: the metabolic score was less than or equal to 1 point than the perfusion score (low perfusion but good metabolism, perfusion/metabolism not matched), the score of ^{99m}Tc-MIBI and ^{18}F-FDG uptake was less than or equal to 2 points, or ^{99m} Tc- MIBI and ^{18}F-FDG uptake was proportional to the seriously sparse or defective, that is, 3 or 4 points, which was considered as non-VM.[7]

2.2.5. Revascularization therapy. Through femoral or radial artery puncture, selective multi-position left and right coronary angiography (CAG) was performed under cardiovascular imaging machine (GE520, USA) about 1 week from AMI occurrence according to the guidelines, 2 or more projection positions were used for CAG. PCI was undertaken in the infarction related artery for coronary stenosis ≥70%. PCI success criteria: postoperative coronary angiography showed recanalization of coronary artery, TIMI grade 3, no residual stenosis, and no significant complications.

2.3. Statistical analysis

Statistical analysis was performed by Statistical Analysis System 9.4 (SAS 9.4, USA). The continuous variables were presented as mean ± standard deviation, and the count data as the number of cases (percentage). The 2 groups of measurement data met the normality and the variance was checked by one way ANOVA, and the 2 groups of measurement data meeting the non-normal distribution were examined by Wilcoxon rank sum test. Receiver-operator characteristics (ROC) curves were created to evaluate the sensitivity, specificity and accuracy of different parameters to predict the VM. Chi-square test was used to compare the 2 groups. Multivariable logistic regression analysis was used to assess the independent predictive value of all parameters. *P* values of .05 were defined as statistically significant. In the parallel test of combining the 2 methods, a positive test resulting with any one of the 2 tests was considered as positive, but in the serial test, the 2 tests must both yield positive results, to be considered as positive.

3. Results

3.1. The clinical data and basic information of 40 patients with EF < 50% (Table 1)

3.1.1. The status and score of LV wall motion. The total 680 segments in 40 patients were viewed by conventional echocardiography, with 20 segments excluded due to poor images. Among the remaining 660 segments, 442 segments were evaluated as normal and 218 segments as segments with RWMA. In the pre-PCI, there were 178 hypokinetic segments, 28 akinetic segments and 12 dyskinetic segments respectively. All patients were examined by routine echocardiography 1, 3, and 6 months post PCI. 127 hypokinetic segments, 9 akinetic segments and 4 dyskinetic segments showed improved score of RWMA with at least 1 point or more respectively, and 51 hypokinetic segments, 19 akinetic segments and 8 dyskinetic segments had no improvement of score. According to the golden standard (the movement of segments with RWMA improved at least 1 scale after PCI), 140 segments were identified as VM and 78 segments as non-VM (Fig. 1). LVEF after PCI was significantly improved (49.95 ± 4.41 vs 41.20 ± 4.46, $P < .05$).

Table 1

The clinical data and basic information of patients with AMI.

Patient history	Value
Mean age (years)	61.0 ± 5.6
Male	27/40 (67.5%)
Hypertension	22/40 (55%)
Diabetes mellitus	18/40 (45%)
Hypercholesterolemia	29/40 (72.5%)
Smoking	24/40 (60%)
LVEF (%)	41.20 ± 4.46
LAD (IRA)	22/40 (55%)
RCA (IRA)	10/40 (25%)
LCX (IRA)	8/40 (20%)
AMI (inferior)	12/40 (30%)
AMI (anterior)	22/40 (55%)
AMI (lateral,high lateral)	6/40 (15%)
AMI (inferior + lateral, inferior+high lateral, anterior + high lateral)	5/40 (12.5%)

The values were expressed as a percentage or mean ± standard deviation.
AMI = acute myocardial infarction, IRA = Infarction related artery, LAD = left anterior descending artery, LCX = left circumflex artery, LVEF = left ventricular ejection fraction, RCA = right coronary artery.

3.2. DISA-SPECT

135 of 218 segments with RWMA were identified to be VM and 83 non-VM by DISA-SPECT. Compared with the gold standard, the sensitivity, specificity and accuracy of DISA-SPECT for evaluating VM were 82.1%, 74.3%, and 79.3%, respectively (Table 2).

3.3. LS2D-STE

All parameters between VM and non-VM had obvious statistical differences (Table 3) except RS and RSr. Analysis of ROC curves showed LS, LSr, CS, and CSr had higher sensitivity, specificity and accuracy than RS and RSr for assessing VM (Table 4, Fig. 4). Multivariable logistic regression analysis suggested that only the endo-LS and endo- LSr were independent parameters for evaluating VM ($P < .05$, Table 5). ROC curve revealed that the optimal cut-off points of endo-LS and endo-LSr were -11.20 and −0.805, respectively. The sensitivity, specificity and accuracy

Table 2

DISA-SPECT compared with the golden standard for evaluating VM (segments).

	Golden standard		Total
DISA-SPECT	VM	Non-VM	
VM	115	20	135
Non-VM	25	58	83
Total	140	78	218

DISA-SPECT = dualisotope simultaneous acquisition single photon emission computed tomography, VM = viable myocardium.

Table 3

S and Sr between VM and non-VM.

Parameters	VM (n = 140)	Non-VM (n = 78)	*P* value
EndoLS (%)	−15.24 ± 6.03	−9.46 ± 5.27	<.01
MidLS (%)	−10.54 ± 5.44	−7.50 ± 3.81	<.01
EpiLS (%)	−7.87 ± 4.47	−6.57 ± 3.63	.04
Total Wall LS (%)	−10.54 ± 5.45	−7.50 ± 3.80	<.01
EndoLSr (s^{-1})	−1.12 ± 0.47	−0.72 ± 0.39	<.01
MidLSr (s^{-1})	−0.73 ± 0.32	−0.53 ± 0.28	<.01
EpiLSr (s^{-1})	−0.61 ± 0.29	−0.49 ± 0.26	<.01
Total Wall LSr (s^{-1})	−0.73 ± 0.32	−0.53 ± 0.27	<.01
EndoCS (%)	−14.23 ± 8.50	−10.80 ± 7.47	<.01
MidCS (%)	−9.75 ± 6.25	−6.73 ± 4.14	<.01
EpiCS (%)	−8.10 ± 5.56	−6.15 ± 4.27	.01
Total Wall CS (%)	−9.75 ± 6.25	−6.73 ± 4.14	<.01
EndoCSr (s^{-1})	−1.15 ± 0.54	−0.83 ± 0.53	<.01
MidCSr (s^{-1})	−0.81 ± 0.40	−0.57 ± 0.33	<.01
EpiCSr (s^{-1})	−0.64 ± 0.42	−0.47 ± 0.34	<.01
Total Wall CSr (s^{-1})	−0.81 ± 0.40	−0.57 ± 0.33	<.01
RS (%)	9.44 ± 21.05	8.71 ± 19.32	.80
RSr (s^{-1})	1.14 ± 0.83	0.99 ± 0.76	.19

$P < .05$ was statistically significant.

endo-RS = mid-RS = epi-RS endo-RSr = mid-RSr = epi-RSr.

CS = circumferential peak systolic strain, CSr = circumferential peak systolic strain rate, LS = longitudinal peak systolic strain, LSr = longitudinal peak systolic strain rate, RS = radial peak systolic strain, RSr = radial peak systolic strain rate, S = peak systolic strain, Sr = peak systolic strain rate, VM = viable myocardium.

of VM evaluation were 77.1%, 65.4%, and 72.9% by endo-LS vs 72.9%, 65.4%, and 69.7% via endo-LSr (Table 4).

3.4. Endo-LS vs total wall-LS and endo-LSr vs total wall-LSr

The endo-LS was superior to total wall-LS for evaluating VM (AUC 0.767 vs 0.669; accuracy 72.9% vs 63.7% Fig. 4F Table 4), and the endo-LSr was also superior to total wall-LSr (AUC 0.743 vs 0.682; accuracy 69.7% vs 67.0% Fig. 4G Table 4).

3.5. LS2D-STE vs DISA-SPECT

The parallel test of combination of endo-LS and endo-LSr showed that the sensitivity, specificity and accuracy rose to 83.5%, 69.2%, and 78.4%, respectively, and the sensitivity, specificity and accuracy of the serial test were 72.8%, 82.0%, and 76.1%, respectively. The parallel and serial tests of combination of endo-LS and endo-LSr showed similar sensitivity, specificity and accuracy to DISA-SPECT (83.5% vs 82.1%, 69.2% vs 74.3%, and 78.4% vs 79.3% in the parallel test; 72.8% vs 82.1%, 82.0% vs 74.3%, and 76.1% vs 79.3% in the serial test; all $P > .05$).

3.6. Reproducibility test

To evaluate the reproducibility, 10 patients were randomly selected. The variables of LS2D-STE were measured repeatedly by 2 dependent observers (interobserver variability). Intraobserver variability was checked by the same observers 4 weeks apart. For the strain and strain rate measurements, the interobserver variability was 6.5% while the intraobserver variability was 5.8%.

4. Discussion

4.1. Definition and value of VM

In some developing countries, the patients with AMI often miss the optimal reperfusion time for the economic and transportation reasons, but they can benefit from delayed PCI because of VM. VM including hibernating stunned myocardium is generally referred to as "alive myocardium", which is an independent contractile status of the myocardium.[16,17] Early recognition of VM has important clinical relevance since affected segments have the potential functional recovery.[18] Therefore, identification of VM before PCI is vital for its capability of improving the prognosis of patients after revascularization.[17]

Previous studies showed that body mass index (BMI), waist circumference (WC) and LVEF could evaluate the cardiac

Table 4

The values of VM evaluated by different parameters.

Parameters	AUC	*P* value	Cutpoint value	Sensitivity (%)	Specificity (%)	Accuracy (%)
LS (endo)	0.767	<.01	−11.20	77.1%	65.4%	72.9%
LS (mid)	0.669	<.01	−9.01	60.0%	70.5%	63.7%
LS (epi)	0.580	.04	−6.03	65.0%	50.0%	59.6%
LS (total)	0.669	<.01	−9.01	60.1%	70.5%	63.7%
LSr (endo)	0.743	<.01	−0.81	72.9%	65.4%	69.7%
LSr (mid)	0.682	<.01	−0.60	67.1%	66.7%	67.0%
LSr (epi)	0.617	<.01	−0.42	70.7%	51.3%	63.8%
LSr (total)	0.682	<.01	−0.60	67.1%	66.7%	67.0%
CS (endo)	0.627	<.01	−13.34	57.9%	68.8%	62.0%
CS (mid)	0.643	<.01	−6.31	68.6%	55.8%	63.7%
CS (epi)	0.605	<.01	−7.48	52.9%	67.5%	57.8%
CS (total)	0.643	<.01	−6.31	68.6%	55.8%	63.7%
CSr (endo)	0.672	<.01	−0.99	61.4%	67.5%	63.3%
CSr (mid)	0.676	<.01	−0.83	47.9%	79.2%	59.2%
CSr (epi)	0.621	<.01	−0.49	60.0%	64.9%	61.5%
CSr (total)	0.676	<.01	−0.83	47.9%	78.2%	58.7%
RS	0.508	.84	14.8	42.9%	65.4%	50.9%
RSr	0.559	.14	1.03	57.1%	61.5%	58.7%

$P < .05$ had statistically significant.

CS = circumferential peak systolic strain, CSr = circumferential peak systolic strain rate, LS = longitudinal peak systolic strain, LSr = longitudinal peak systolic strain rate, RS = radial peak systolic strain, RSr = radial peak systolic strain rate, VM = viable myocardium.

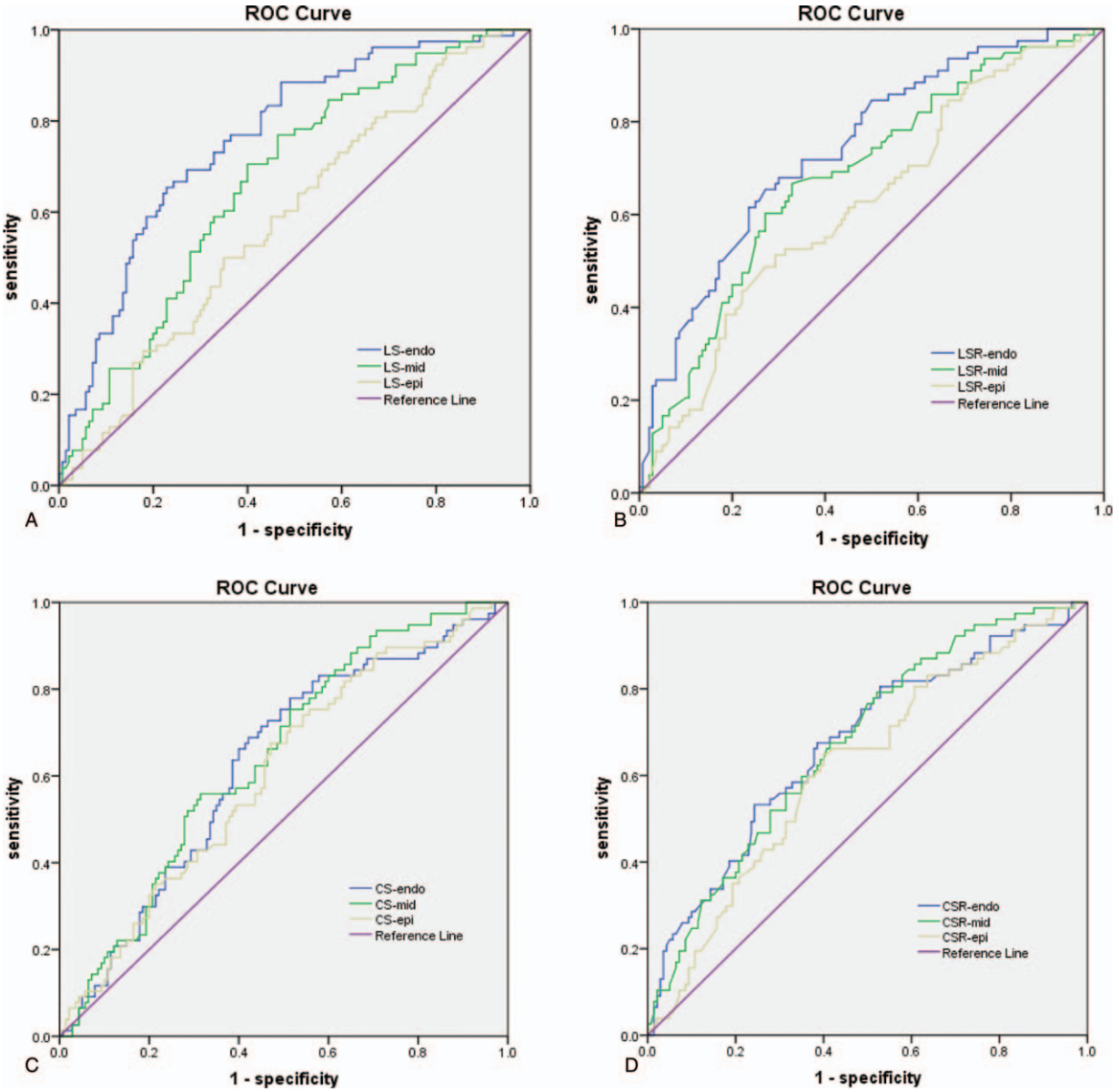

Figure 4. (A–E) the sensitivity, specificity and accuracy of layer-specific strain and strain rate for evaluating VM. (F) LS-endo vs LS-total wall for evaluating VM. (G) LSR-endo vs LSR-total wall for evaluating VM.

function early.[19] Currently, PET and echocardiography were recognized as the golden standards for VM, but PET was restricted in clinical research, so the follow-up of the routine echocardiography was considered as the golden standard for VM.[20] With the improvement of VM after PCI, LVEF and RWMA can be significantly improved and delayed occurs,[21] so we followed up echocardiography 1, 3, and 6 months after PCI, which avoided the influence of the restenosis of the stent.

Our study chose the patients who had missed the optimal reperfusion time, because the prognosis of such patients were poor, early noninvasive evaluation of VM was particularly important for the benefit of delayed PCI.

4.2. Imaging technology for assessing VM

PET and cardiac MRI as non-invasive and accurate methods to detect VM were restricted because of its high cost.[22,23] Previous studies have shown that DISA-SPECT as a widely recognized new technology to explore VM has no significant difference in sensitivity and specificity compared with PET in the assessment of VM.[24] The sensitivity of DISA-SPECT for detecting VM was 71% to 100%, and the specificity was 38% to 91%.[25] This study showed that the sensitivity and specificity of DISA-SPECT were 82.1% and 74.3% in consistency with previous studies. It is clear that DISA-SPECT could be used as a convincing technique to assess VM when PET is not available, but it cannot be widely used due to its radiation exposure, equipment requirements and high cost, nor could it be carried out bedside.

4.3. 2D-STE for assessing VM

It is particularly important to find a low-cost, non-invasive, and no-radiation method to assess VM. DSE is a non-invasive method to evaluate VM,[26,27] but it has strong subjectivity, calling for

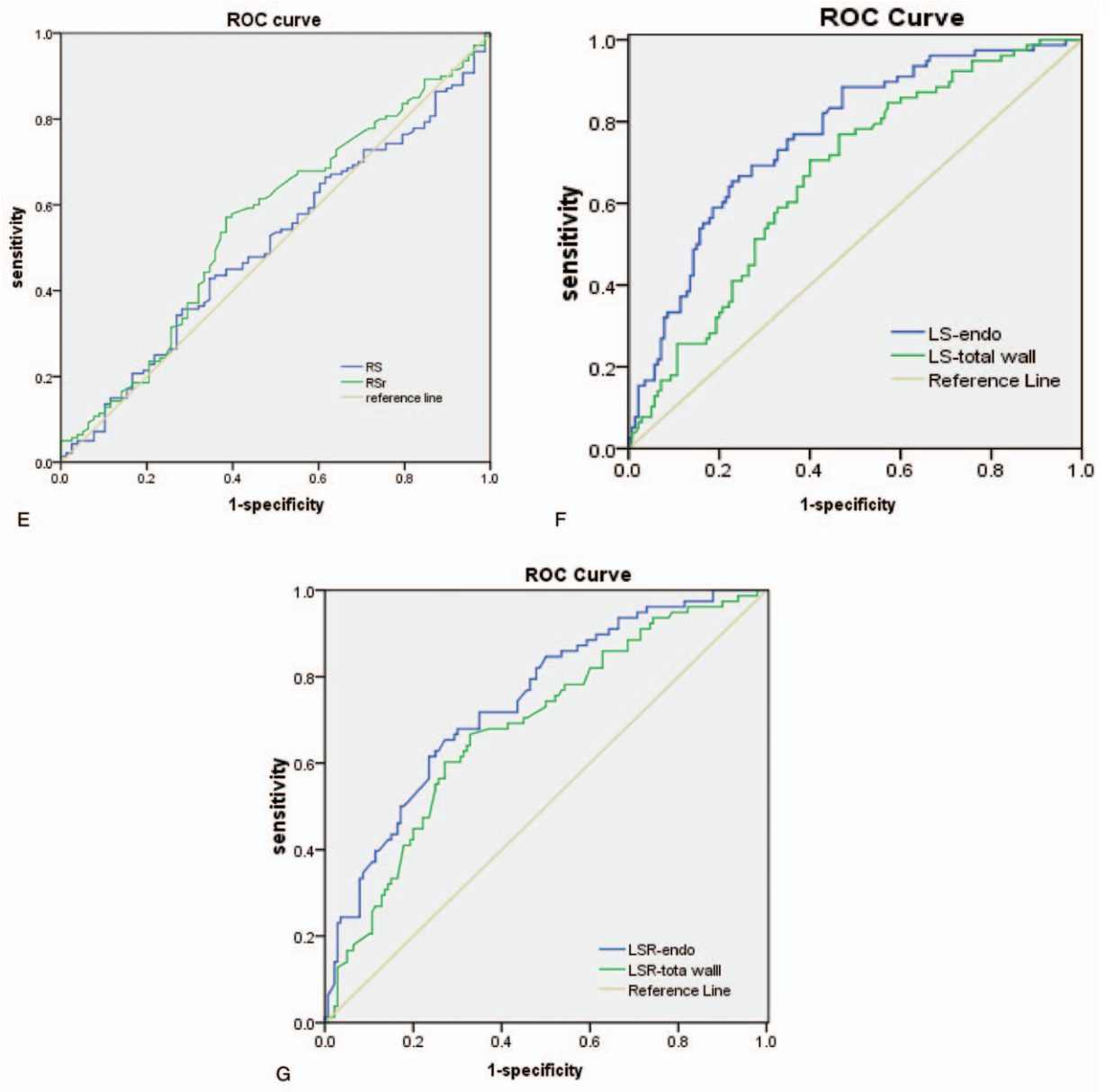

Figure 4. (Continued).

higher professional experience, and its sensitivity and specificity change greatly.[28] 2D-STE is widely used in clinics as a new high-quality analytical technique. Compared with conventional TDI, STE overcomes the angle dependence and requires no high frame rate, and the deformation of myocardial fibers in longitudinal, circumferential and radial directions could be measured.[29,30] 2D-STE is used to evaluate VM by measuring the LV global and regional strain and strain rate recently.[31,32] Some studies have shown that 2D-STE has high sensitivity and appropriate specificity for early identification of VM in patients with AMI by strain and strain rate measurements.[33]

4.4. LS2D-STE for evaluating VM

Previous studies on detection of VM by 2D-STE evaluated the left ventricle as a whole,[34] but the left ventricular myocardium is divided into 3 layers, namely the spiral muscle bundle of the inner and outer layers and the circular muscle bundle of the middle layer.[35] The division of the myocardial layer is not clear-cut and absolute layers of fibers are not isolated, and they affect each other.[36] Previous analyses have proved that different diseases could injure the myocardial layers to different extents and could result in alternated predominant dysfunction in specific layers.[37,38] Apparently, evaluation of myocardial deformation just across the ventricular wall thickness is not able to provide comprehensive information on the cardiac function.[39]

But recently LS2D-STE was used to predict the severity of coronary lesions.[40,41] To the best of our knowledge, this study is the first to predict VM using layer-specific strain and strain rate measured by LS2D-STE in patients with AMI. Our study showed that:

1. LS, LSr, CS and CSr gradually decreased from the endocardium to the epicardium, which was consistent with the previous study.[36]

Table 5

Results of multivariate logistic regression analysis.

Parameters	Estimated value	Standard error	Wald χ^2	*P*	OR95%CI
LS (endo)	0.098	0.036	7.404	.007	1.103 (1.028,1.184)
LS (mid)	0.066	0.045	2.169	.141	1.068 (0.978,1.166)
LS (epi)	−0.028	0.048	0.338	.561	0.973 (0.886,1.068)
LS (total)	0.067	0.045	2.168	.141	1.068 (0.978,1.166)
LSr (endo)	0.974	0.474	4.218	.040	2.648 (1.045,6.709)
LSr (mid)	0.829	0.644	1.654	.198	2.290 (0.648,8.097)
LSr (epi)	0.114	0.693	0.027	.869	1.121 (0.288,4.363)
LSr (total)	0.829	0.645	1.654	.198	2.290 (0.648,8.097)
CS (endo)	0.026	0.025	1.079	.299	1.027 (0.977,1.079)
CS (mid)	0.032	0.043	0.541	.462	1.032 (0.949,1.123)
CS (epi)	−0.016	0.044	0.138	.710	0.984 (0.902,1.073)
CS (total)	0.032	0.043	0.541	.462	1.032 (0.949,1.123)
CSr (endo)	0.729	0.390	3.493	.062	2.073 (0.965,4.451)
CSr (mid)	0.661	0.558	1.405	.236	1.936 (0.649,5.775)
CSr (epi)	0.309	0.550	0.315	.575	1.362 (0.463,4.001)
CSr (total)	0.661	0.558	1.405	.236	1.936 (0.649,5.775)
RS	0.002	0.007	0.065	.799	1.002 (0.988,1.016)
RSr	0.227	0.176	1.662	.197	1.255 (0.888,1.773)

$P < .05$ had statistically significant.

CS = circumferential peak systolic strain, CSr = circumferential peak systolic strain rate, LS = longitudinal peak systolic strain, LSr = longitudinal peak systolic strain rate, RS = radial peak systolic strain, RSr = radial peak systolic strain rate.

2. The endo-LS and endo-LSr were independent parameters for predicting VM, with the sensitivity, specificity and accuracy of endo-LS and endo-LSr being 77.1%, 65.4%, 72.9% and 72.9%, 65.4%, 69.7%, respectively.

3. The parallel test and the serial test of combination of endo-LS and endo-LSr showed higher sensitivity, specificity and accuracy than single index. Because the heart muscle is composed of 3 layers, and the endocardial layer is known as the most susceptible and the first component of the ischemic cascade.[42]

Ono et al reported that endocardial layer is first affected by ischemia,[43] causing morphologic and functional alterations predominant in this layer in myocardial infarction models.[44] The endocardial layer is most sensitive to ischemia in patients with AMI. Reant et al found that good correlation was observed between strain and myocardial deformation parameters in an animal model, and LS was the best, followed by CS and RS.[45] Howard et al also showed that LS was more sensitive to ischemia, being able to detect changes in LV function.[46] The innermost subendocardial layer of fibers showed an oblique clockwise orientation in the longitudinal direction, with the most significant contribution to long-axis function. The middle layer was wrapped circumferentially, and the epicardial layer was arranged in an oblique anticlockwise direction. It contributes to thickening and short-axis function via cross-fiber shortening.[47,48] Because of the unique structure, the endo-LS and endo-LSr can be used to assess VM better than other parameters.

4.5. Layer-specific vs total wall thickness

Becker et al showed that layer-specific analysis allowed accurate discrimination between different transmurality categories of myocardial infarction and appears to be superior to total wall thickness myocardial deformation analysis.[49] Altiok et al found that the analysis of endocardial layer peak circumferential strain was superior to transmural strain analysis for the identification of myocardial segments with functional improvement.[8] In our study the endo-LS and endo-LSr as independent parameters for predicting VM were superior to total wall thickness LS and LSr, probably at acute stages of AMI, before collagen deposition, scar tissue formation, and remodeling have occurred, damage may be nontransmural.[50]

4.6. LS2D-STE vs DISA-SPECT

A previous study showed that the sensitivity of STE combined with DSE was similar to DISA-SPECT for evaluating VM in the patients with AMI,[34] and our study showed that the parallel and serial tests of STE-based endo-LS and endo-LSr showed similar sensitivity, specificity and accuracy to DISA-SPECT ($P > .05$).

This study showed that RS and RSr were inferior to LS, LSr, CS, and CSr for assessing VM, because RS has methodological limitations, and it has been shown to be inferior to longitudinal and circumferential strain in identifying ischemia and necrosis.[51] We found that RS and RSr had greater variability, which was consistent with previous studies, but the exact reason was uncertain.[52]

In a word, LS2D-STE as a novel method could evaluate VM in an economic, non-invasive, and pollution-free manner at the early stage of AMI; it offers us a good alternative for assessing VM, judging the prognosis of patients and guiding PCI treatment.

4.7. Study limitations

Firstly, the sample size of this study was small, and the accuracy of STE and DISA-SPECT was influenced by the quality of 2D image, arrhythmia, obesity, artificial valves, and hyperglycemia. There were more LAD lesions as infarction-related arteries in this study (22/40), which may have had an impact on the result. Secondly, because of continuity of myocardial fibers, the deformation parameters of the 3 layers were not completely isolated and absolute, and they influenced each other. In some patients with AMI, the ventricular wall became thinner, making it difficult for LS2D-STE to distinguish the 3 layers, so we had to depend on manual adjustment, which we are supposed to improve in future research. With the application of 3-dimensional

speckle tracking echocardiography (3D-STE) and mesh-free method, VM will be evaluated more accurately in the future.[53,54]

5. Conclusions

LVEF may improve significantly after PCI in patients with AMI, the endo-LS and endo-LSr of LS2D-STE could evaluate VM well, and the parallel test and the serial test of combination of endo-LS and endo-LSr show similar sensitivity, specificity and accuracy to DISA-SPECT. It offers us a good alternative for assessing VM.

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Author contributions

Dongye Li conceived of the study, Kun Liu performed the experiments and draft the manuscript. Yan Wang and Peng Chen performed the experiments. Gonghao Li carried out the statistical analysis. Qiongyu Hao helped to draft the manuscript. All authors read and approved the final manuscript.
Data curation: Yan Wang.
Formal analysis: Gonghao Li.
Funding acquisition: dongye li.
Investigation: Dongye Li, Kun Liu.
Methodology: Kun Liu, Yan Wang, Peng Chen.
Project administration: Dongye Li, Kun Liu, Peng Chen.
Resources: Kun Liu, Peng Chen.
Supervision: Dongye Li.
Writing – original draft: Kun Liu.
Writing – review & editing: Kun Liu, Qiongyu Hao.

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