Detection and Quantification of Myocardial Scars by Contrast-Enhanced 3D Echocardiography

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Background—Myocardial infarcts are usually imaged by delayed-enhanced cardiac magnetic resonance (DE-cMR). In this study, we tested the hypothesis that the detection and quantification of myocardial scars can be evaluated by 3D echocardiography (3D-echo).

Methods and Results—Fifty patients with a healed myocardial infarction (>3 months) and 10 controls underwent 3D echo and DE-cMR within 2 weeks. 3D-echo images were acquired with different settings, with or without contrast. The highest contrast-to-noise ratio was obtained with second-harmonic imaging (1.6/3.2 MHz), at a mechanical index of 0.5, in the presence of contrast. Using this modality, we calculated the sensitivity and specificity of the 3D-echo detection of cMR scars on a segmental basis to be 78% and 99%, respectively. On a per-patient basis, they were 96% and 90%, respectively. Good correlation and limits of agreement were found between the assessment of scar mass by 3D echo and DE-cMR (r=0.93, P<0.001; bias, 1.4±3.6 g), and the concordance between both techniques for the assessment of scar transmurality was good. Intraobserver, interobserver, and day-to-day reproducibility was comparable between 3D echo and DE-cMR for both the detection and quantification of scars.

Conclusions—Contrast-enhanced 3D echo is a promising new tool for the detection and quantification of myocardial infarct scars. (Circ Cardiovasc Imaging. 2010;3:415-423.)

Key Words: echocardiography  ■  MRI  ■  myocardial infarction

In patients with coronary artery disease and chronic left ventricular (LV) dysfunction, the distinction between reversible and irreversible myocardial injury is of paramount clinical importance,1,2 because only those patients with reversibly injured or viable myocardium can experience an increased LV ejection fraction3 and improved survival after revascularization.4,5

Clinical Perspective on p 423

Noninvasive methods for assessing myocardial viability include positron-emission tomography, single-photon-emission computed tomography, and dobutamine echocardiography (echo).2 These techniques have proven clinical utility, but each has limitations that may reduce its diagnostic accuracy. For example, they only interpret myocardial viability as an all-or-none phenomenon within a given myocardial region, and none of them assesses the transmural extent of viability across the ventricular wall. Because gadolinium accumulates in scar tissue, delayed-enhanced cardiac magnetic resonance (DE-cMR) has been proposed to delineate the transmural extent of infarction and to distinguish reversible from irreversible myocardial injury.6,7 Both experimental and clinical studies have validated this concept, allowing DE-cMR to progressively become the reference method for assessing the transmural extent of necrosis and, by inference, myocardial viability.

Several previous studies have shown that, in patients with prior myocardial infarction, myocardial scar tissue usually appears brighter than normal myocardium on diagnostic echocardiographic images, the intensity of the backscattered echo signals being proportional to the amount, orientation, and compactness of the underlying collagen fibers.8,9 Although both M-mode and 2-dimensional (2D) echo allow for the detection of the presence of myocardial scar,10,11 the information provided by these modalities is seldom used clinically, owing probably to their inability to...
delineate the 3-dimensional (3D) extent of the pathological process.

Recently, 3D echo was introduced as a promising new method for assessing LV morphology, volumes, and mass in patients with structural heart disease. When used in combination with computerized endocardial contour tracking algorithms, it indeed permits faster, more accurate, and less operator-dependent quantification of LV volumes and mass than either 1-dimensional echo or 2D echo. In this study, we sought to determine whether 3D echo could be used to evaluate the presence and extent of myocardial scars.

Methods

Patients

We prospectively recruited 63 subjects in sinus rhythm to undergo DE-cMR and 3D-echo in random order within 2 weeks. Subjects with constant arrhythmia or any contraindication to cMR were not considered for inclusion. Of the initial 63 subjects, 3 could not complete the cMR study (2 because of claustrophobia, 1 because of an adverse reaction to the gadolinium contrast agent) and were therefore excluded from the analysis.

Of the 60 remaining subjects (46 men; mean±SD age, 63±14 years; range, 25 to 84 years), there were 50 patients with coronary heart disease and a prior myocardial infarction (40 men; mean±SD age, 66±11 years; range, 41 to 84 years) and 10 volunteers (6 men; mean±SD age, 50±19 years; range, 25 to 72 years). Patients with prior myocardial infarction were selected from the single-photon-emission computed tomography database at our institution. Inclusion criteria were the presence of a fixed perfusion defect and a clinical diagnosis of a previous myocardial infarction, at least 3 months old, in the same anatomic distribution as the single-photon-emission computed tomography perfusion defect. Inclusion criterion for normal volunteers was the absence of heart disease based on history, ECG, rest echo, and maximal exercise test. The study protocol was approved by the ethics committee at our institution, and all patients gave informed consent before inclusion into the study.

3D-Echo

3D-echo was performed with an IE33 echocardiographic system (Philips, Andover, Mass) equipped with a broadband, wide-angle, matrix-array transducer. The 3D-echo datasets were acquired from the apical window with an ECG-triggered, wide-angle acquisition (93°×80°) mode in which 4 wedge-shaped subvolumes were obtained over 4 consecutive cardiac cycles during a short breath-hold. Care was taken to include the entire left ventricle within the pyramidal scan volume.

Delayed-Enhanced Cardiac Magnetic Resonance

cMR was performed in a 1.5-T magnet (Philips, Eindhoven, The Netherlands) with a phased-array coil wrapped around the chest. After localization of the heart, patients received an intravenous bolus of 0.1 mmol/kg gadobenas dimeglumine (Bracco Altana Pharma GmbH, Konstanz, Germany). Fifteen minutes later, delayed images were acquired in the apical 2-, 3-, and 4-chamber projections. In patients with a prior myocardial infarction, the cropped planes were carefully chosen to pass through the infarct area. The so-obtained cropped 2D images were then saved as uncompressed files onto the hard drive and were subsequently analyzed with ImageJ software (version 1.38, National Institutes of Health, Bethesda, Md). This software allows for the manual contouring of endocardial and epicardial borders as well as that of any hypoenhancing area. As with DE-cMR, myocardial scar tissue was identified as areas of increased subendocardial or transmural brightness. In brief, the 3D-volume dataset was first displayed in 3 different cross sections that can be modified interactively. For the detection algorithm to work properly, the anatomically correct 4- and 2-chamber views need to be displayed simultaneously. Markers were then placed onto the mitral annulus and the apex, both in end diastole and end systole. With these markers, the software program first creates truncated ellipsoidal end-diastolic and end-systolic 3D meshes of the left ventricle. The vertices of these meshes are then automatically fitted to the image borders (3D gradient of image intensity) while respecting prespecified surface smoothing constraints (to minimize local curvature on the surface). The end-diastolic and end-systolic 3D meshes deform until equilibrium is reached between closeness to the borders and minimal curvature. If needed, manual adjustments were applied. The end-diastolic epicardial contours were next automatically estimated by adding a fixed myocardial wall thickness of 8.8 mm to the endocardial mesh. Manual corrections were applied, if needed. These epicardial contours are used to delineate and calculate the volume of the myocardium. Finally, the software program automatically contours the hypoenhancing areas within the end-diastolic myocardial volume to delineate myocardial scars. Here also, manual corrections were applied, if needed. From these contours, the mass of scar tissue was computed and expressed either in absolute terms (assuming a density of 1.05 g/mL) or as a percentage of the total LV mass. The software also allows for the computation of the transmural extent of the scar tissue on a segmental basis (with the American Society of Echocardiography (ASE) 16 segment model), either as a percentage of the segmental mass or as a fraction of the regional wall thickness.

For the determination of contrast-to-noise ratio (CNR), end-diastolic datasets were first cropped in QLab to obtain 10-mm-thick slices in the apical 2-, 3-, and 4-chamber projections. In patients with a prior myocardial infarction, the cropped planes were carefully chosen to pass through the infarct area. The so-obtained cropped 2D images were then saved as uncompressed files onto the hard drive and were subsequently analyzed with Imaged software (version 1.38, National Institutes of Health, Bethesda, Md). This software allows for the measurement of videointensity (VI) in manually traced regions of interest. Regions of interest were positioned onto the scar area, the normal myocardium, the LV cavity, the pericardium, and the septal stripe, if present. CNRs were calculated as the differences in VI between regions of interest divided by 256 and expressed in percentages.

Data Analysis

All images, irrespective of their quality, were blindly analyzed by 2 observers with at least 2 years of experience in reading 3D-echo and cMR studies (P.M. and F.C.). For this purpose, the images were first anonymized. Image analyses were then randomly performed, in separate sessions for 3D-echo and cMR, to avoid recalling the patients' images. The main results were generated by 1 observer (P.M.). The second observer (F.C.) analyzed a subset of data for assessment of interobserver reproducibility.

Contrast-Enhanced 3D-Echo

All 3D-echo datasets were analyzed with a prototype version of QLab software (version 6.0, Philips Medical Systems, Eindhoven, The Netherlands), which allows for the manual contouring of endocardial and epicardial borders as well as that of any hypoenhancing area. As with DE-cMR, myocardial scar tissue was identified as areas of increased subendocardial or transmural brightness. In brief, the 3D-volume dataset was first displayed in 3 different cross sections that can be modified interactively. For the detection algorithm to work properly, the anatomically correct 4- and 2-chamber views need to be displayed simultaneously. Markers were then placed onto the mitral annulus and the apex, both in end diastole and end systole. With these markers, the software program first creates truncated ellipsoidal end-diastolic and end-systolic 3D meshes of the left ventricle. The vertices of these meshes are then automatically fitted to the image borders (3D gradient of image intensity) while respecting prespecified surface smoothing constraints (to minimize local curvature on the surface). The end-diastolic and end-systolic 3D meshes deform until equilibrium is reached between closeness to the borders and minimal curvature. If needed, manual adjustments were applied. The end-diastolic epicardial contours were next automatically estimated by adding a fixed myocardial wall thickness of 8.8 mm to the endocardial mesh. Manual corrections were applied, if needed. These epicardial contours are used to delineate and calculate the volume of the myocardium. Finally, the software program automatically contours the hypoenhancing areas within the end-diastolic myocardial volume to delineate myocardial scars. Here also, manual corrections were applied, if needed. From these contours, the mass of scar tissue was computed and expressed either in absolute terms (assuming a density of 1.05 g/mL) or as a percentage of the total LV mass. The software also allows for the computation of the transmural extent of the scar tissue on a segmental basis (with the American Society of Echocardiography (ASE) 16 segment model), either as a percentage of the segmental mass or as a fraction of the regional wall thickness.

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Delayed-Enhanced cMR
DE-cMR datasets were transferred to a computer workstation and analyzed with Segment software (version v1.691, Einar Heiberg), which allows for the semiautomatic detection of hyperenhanced areas. In brief, the endocardial and epicardial LV contours were first manually traced on each consecutive short-axis slice. The software program then divides the myocardial volume into 6 segments per slice. Manual adjustments were applied, if needed. The images were then binarized to a threshold of 2 standard deviations of the mean value obtained in 9 remote normal segments without hyperenhancement. The transmural extent of hyperenhancement was then computed within each segment on these thresholded images and reported as the percentage of the segmental area that is hyperenhanced. The scar mass, expressed in absolute term (assuming a density of 1.05 g/mL) or as a percentage of the total LV mass, was computed by Simpson’s method. The transmural extent of hyperenhanced areas was computed on a segmental basis (with the ASE 16-segment model) as a fraction of the segmental wall thickness. Finally, the software also allowed computation of LV volumes and ejection fraction.

Statistical Analysis
Statistical analyses were performed with SPSS (version 12.0) software (SPSS Inc, Chicago, Ill). Values are reported as mean±SD. McNemar test was used to compare DE-cMR and contrast-enhanced (CE) 3D-echo by the Bland-Altman method. Differences in mean measurements between the 2 modalities were compared by Student t test. Intraobserver, interobserver, and test-retest reproducibility of scar quantification was assessed with 2-way random single-measure intraclass correlation coefficients and the Bland-Altman method. For this purpose, 20 datasets were randomly chosen at the end of the recruitment period to assess intraobserver and interobserver reproducibility. Test-retest reproducibility was investigated from the data of the first 10 patients who consented to undergo CE-3D-echo and DE-cMR twice on 2 consecutive days. The transmural extent was compared by χ2 statistics. All tests were 2 sided, and P<0.05 was considered to indicate statistical significance.

Results
In the 50 patients with prior myocardial infarction, infarct age was 6±7 years (median, 2.7 years; range, 3 months to 34 years). The area of necrosis involved the anterior wall in 18 (36%), the lateral wall in 3 (6%), and the inferior and/or posterior wall in 29 (58%). Mean LV ejection fraction was 44±13% by 3D-echo and 43±14% by cMR. CE-3D-echo slightly, albeit nonsignificantly, underestimated end-diastolic and end-systolic volumes, compared with values obtained by cMR (180±60 vs 191±67 mL and 106±55 vs 116±66 mL, respectively). Body mass index was 25±5 kg/m² (range, 18 to 43 kg/m²).

VI and CNRs
Figure 1 shows the changes in VI in normal myocardium and scar segments in second-harmonic mode at increasing MI. As illustrated, the increase in VI was larger in scar segments than in normal myocardium, reaching saturation at an MI of ~0.5. Similar results were obtained for each of the pulse emission frequencies and pulse cycle lengths tested and were independent of the use of power modulation. Use of contrast markedly increased VI in the LV cavity, increased VI at only high Mls in normal myocardium, and did not modify VI in infarcted myocardium.

Figure 2 shows the effects of changing the MI, the pulse emission frequency, the pulse cycle length, or the pulse repetition on CNRs between scar tissue and surrounding structures (ie, normal myocardium and LV cavity). As illustrated, in both unenhanced and CE datasets, the highest CNRs were obtained with harmonic imaging. Although the use of contrast was associated with significant decreases in CNRs, it allowed for a better delineation of endocardial contours and hence, for a better appreciation of the transmural extent of the scar tissue. This is illustrated in Figure 3. Accordingly, we opted both for the use of contrast in the second part of our study and imaging in the second-harmonic mode, with an emission frequency of 1.6 MHz at an MI of 0.5, as this imaging modality was associated with the highest CNRs in the presence of contrast (Figure 2). CNRs obtained with this modality were not significantly different from those obtained with DE-cMR (CNR between scar and normal myocardium, 60±6% vs 63±20%, respectively; P=0.8; CNR between scar and LV cavity, 29±11% vs 20±13%, respectively; P=0.065).

Detection of Myocardial Scars by CE-3D-Echo
Figure 4 shows representative CE-3D-echo and DE-cMR images in 3 patients with areas of hyperenhancement by DE-cMR in the anterior, inferior, and lateral walls, respectively. As shown in Table 1, on a segmental basis, DE-3D-echo allowed the identification of DE-cMR scars with a sensitivity of 78% (95% CI, 73% to 84%), a specificity of 99% (95% CI, 98% to 100%), and an overall accuracy of 94% (95% CI, 92% to 95%). There were a total of 51 false-negative segments, among which 44 presented with subendocardial scars (86%, mean transmural extent of 26±13%), and 35 (69%) were located in the anterior or lateral segment. There were also 9 false-positive segments, all located in the septum. Figure 5 shows representative false-positive and false-negative CE-3D-echo results. When data were analyzed...
on a per–vascular territory basis, the sensitivity and specificity of CE-3D-echo for identification of DE-cMR scars were, respectively, 95% (95% CI, 91% to 99%; 113/119 segments) and 100% (181/181 segments) in the inferior and posterior walls; 68% (95% CI, 58% to 78%; 57/84 segments) and 98% (95% CI, 96% to 99%; 387/396 segments) in the anterior, anteroseptal, and septal walls; and 48% (95% CI, 31% to 66%; 16/33 segments) and 100% (147/147 segments) in the lateral wall.

On a per-subject basis, 2 patients (with small subendocardial scars of 2.7 and 5 g, respectively) were missed by CE-3D-echo. False-positive results were found in only 1 subject, yielding a sensitivity of 96% (95% CI, 91% to 99%; 48/50 patients), a specificity of 90% (95% CI, 71% to 99%; 9/10 control subjects), and an overall accuracy of 95% (95% CI, 91% to 99%; 57/60 subjects).

Septal Wall
Because all false-positive segments were located within the septum and potentially related to the presence of septal stripes, we further investigated all bright septal areas (BSAs).

Figure 2. Line plots showing the changes in CNR between scar tissue and the LV cavity (left) and between scar tissue and normal myocardium (right). The upper panels show the data obtained without contrast, whereas the lower panels show the data obtained during contrast infusion.

Figure 3. Comparison of unenhanced (left) and CE (right) 3D-echo in a patient with a 20-month-old posterior myocardial infarct. On both images, 3 areas of brightness can be identified (at 2, 5, and 9 o’clock). Only the CE image allows identification of these areas as the pericardium, a subendocardial scar, and a midwall septal stripe, respectively.
3.3±0.4 to 5.1±1.3 mm for the left-sided hypoechoic band; all P<0.001). None of the type 1 BSAs showed DE-cMR enhancement and were equally prevalent in patients (32%) and controls (30%). In the remaining 18 subjects, BSAs were located in the LV subendocardium, without any hypoechoic band on the left side (type 2). In 7 subjects (9 segments), the subendocardial BSAs thickened during systole (from 3.8±0.9 to 5.2±0.7 mm, P<0.001), became located in the middle of the septum, and were surrounded by 2 hypoechoic bands. On DE-cMR, none of these segments showed hyperenhancement (type 2A). In the remaining 11 subjects, BSAs did not thicken (from 5.2±1.4 to 5.3±1.5 mm, P=0.9), remained located in the subendocardium at end systole, and always exhibited subendocardial DE-cMR hyperenhancement (type 2B).

Delineation of the Transmural Extent of Myocardial Scar by CE-3D-Echo

As shown in Table 1, the agreement between CE-3D-echo and DE-cMR for assessment of the transmural extent of scar was good. Only 16 segments were misclassified by CE-3D-echo. In 14 of these segments, the transmural extent of scar was close to 50% by both techniques (CE-3D-echo, 46±12% vs DE-cMR, 52±13%).

Quantification of Scar Mass by CE-3D-Echo

Absolute scar mass was 12±9 g (median, 12 g) by CE-3D-echo and 13±9 g (median, 15 g) by DE-cMR. Expressed as a percent of LV mass, scar mass was 9±7% (median, 9%) by CE-3D-echo and 10±7% (median, 10%) by DE-cMR. Good correlation and limits of agreement were found between quantitative measures of scar mass by CE-3D-echo and DE-cMR, both in absolute (mean difference of 1.4±3.6 g; 95% CI, −5.7 to 8.5 g; Figure 6) and relative (mean difference of 0.6±3.0%; 95% CI, −5.3 to 6.5%) terms.

Intraobserver, Interobserver, and Test-Retest Reproducibility

Table 2 summarizes the results of these comparisons, by intraclass correlation coefficients and limits of agreement.

Discussion

Clinical studies have shown that the transmurality of myocardial scars is critical in determining the recovery of function after revascularization: the more transmural the extent of scar tissue, the lower the likelihood of recovery in function.18–20

Until recently, DE-cMR was the only available imaging modality allowing for the identification and separation of subendocardial and transmural scars. On imaging, the scar tissue appears white (hyperenhanced), whereas normal myocardium appears dark.6 Because of its high spatial resolution, its excellent CNR, and its intrinsic 3D nature, DE-cMR has progressively become the most popular method for assessing the presence and extent of myocardial scars. Because myocardial scar tissue appears much brighter than normal myocardium on diagnostic echocardiographic images,10,11 we tested the hypothesis that 3D-echo would also be able to detect the presence and quantify the extent of myocardial scars. Our results can be summarized as follows:

Table 1. Presence of Subendocardial (<50% of Wall Thickness) or Transmural (>50%) Scar on a Segmental Basis by CE-3D-Echo and Comparison With DE-cMR

<table>
<thead>
<tr>
<th>CE-3D-Echo</th>
<th>DE-cMR</th>
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<tbody>
<tr>
<td>Absent</td>
<td>715</td>
<td>44</td>
<td>7</td>
</tr>
<tr>
<td>Subendocardial</td>
<td>9</td>
<td>116</td>
<td>11</td>
</tr>
<tr>
<td>Transmural</td>
<td>0</td>
<td>5</td>
<td>53</td>
</tr>
<tr>
<td>Total</td>
<td>724</td>
<td>165</td>
<td>71</td>
</tr>
</tbody>
</table>

Figure 4. Representative CE-3D-echo and DE-cMR images in 3 patients with an old myocardial infarct and 1 control subject. A, One-year-old anterior myocardial infarct; B, 1.5-year-old inferior myocardial infarct; C, 10-year-old lateral myocardial infarct; D, control subject.
Myocardial scars reflect ultrasound more effectively than does normal myocardium. At any MI, the VI measured in myocardial scars is higher than in normal myocardium. When the MI is progressively increased, the increase in VI is also greater in myocardial scars than in normal myocardium.

(2) CNRs between myocardial scars and normal myocardium are the highest when imaging in the second-harmonic mode, with an emission frequency of 1.6 MHz and an MI of 0.5.

(3) The use of contrast reduces CNRs between myocardial scars and normal myocardium but facilitates endocardial and epicardial border recognition and hence, determination of the transmural extent of the scar process.

(4) CE-3D-echo allows identifying myocardial scars with good sensitivity and specificity compared with DE-cMR and also allows for a reasonably accurate quantification of scar tissue (mass and transmural extent). Results are nonetheless better in the inferior/posterior walls than in the anterior/lateral walls.

Delineation of Scar Tissue by Echo

The daily clinical experience in echocardiographic laborato-
ries indicates that the hearts of patients with a prior myocar-
dial infarction demonstrate not only abnormalities of LV wall
motion and thickening but also enhanced intensity of the
reflected echo signals. Back in 1976, Rasmussen et al10 were
the first to report on the presence of areas of increased echo
density on M-mode echocardiograms and to demonstrate a
high degree of correlation with the presence or absence of
scar at surgery or autopsy. Subsequently, in vitro and in vivo
experiments have shown that the acoustic reflectivity of
infarcted myocardium and its transmural extent are a function
of time. In 26 dogs undergoing left anterior descending
coronary artery occlusion, Parisi et al11 reported that infarcted
segments exhibited a progressive increase in echo intensity
that became maximal 6 to 8 weeks after coronary ligation.
Histopathologic and histochemical studies verified that these
increases in echo amplitude were correlated with the evolu-
tion of healing and myocardial scar formation. At 6 to 8
weeks, the mean collagen content of infarcted myocardium
had increased by a factor of 4; concurrently, the echo
amplitude in the infarcted segments had increased 2- to
3-fold. More recently, Tabel et al9 demonstrated that the
intensity of the echo signals reflected by the infarcted
myocardium depended not only on collagen content but also
on collagen fiber morphology. Specifically, these authors
observed that infarcted segments containing mainly thick
collagen fibers were much more echogenic than those contain-
ing predominantly thin collagen fibers. This probably
explains why recently infarcted segments usually appear
normoechoic, whereas older infarcts appear much brighter.
During the complex repair process that is initiated after
myocardial infarction, the development of scar indeed begins
with the production of thin collagen fibers. During the course
of several weeks, these fibers mature, becoming thicker and
more densely packed.

The results of the present study confirm those of these prior
reports and extend them to the use of 3D-echo. Like previous
investigators, we observed that the intensity of the reflected echo signals was larger in infarcted than in normal myocardium. We also observed that the response of infarcted and normal myocardium to increasing MI was different, the intensity of the reflected echo signals increasing much faster in infarcted myocardium to reach saturation for an MI of \( \approx 0.5 \). As the MI-dependent increase in echo signal intensity was much flatter in normal myocardium, the CNRs between infarcted and normal myocardium progressively improved when MIs were increased from 0 to 0.5 and declined thereafter. These observations thus suggest that intermediate MI levels (ie, 0.5) should be used for optimal delineation of infarcted and normal myocardium when imaging the heart in 3D. However, at such low MI levels, the intensity of the echo signals reflected by normal myocardium is very low and limits our ability to appropriately delineate endocardial and epicardial contours and hence, to appreciate the transmural extent of infarction (Figure 2). To overcome this limitation, one can either modestly increase the MI to better visualize the tissue or use ultrasound contrast agents to improve border definition. Because at an MI of 0.5 the presence of contrast did not significantly modify the signal intensity in normal myocardium but greatly enhanced border definition, we elected to use contrast in the validation experiments.

Comparison Between CE-3D-Echo and DE-cMR in Patients With Old Myocardial Infarctions

In the present study, we used DE-cMR as the reference method to which CE-3D-echo was compared. Our results show that the agreement between the 2 methods was quite good. On a segmental basis, the ability of CE-3D-echo to identify DE-cMR scars was high, with positive and negative predictive values well above 90% (95±1% and 93±1%, respectively). Fifty-one infarcted segments by DE-cMR were nonetheless missed by CE-3D-echo. These false-negative segments were more likely to be found in the anterior and lateral walls, where dropout artifacts are frequent and most often presented with small transmural extent of scars (26±13%). Accordingly, the segmental sensitivity of CE-3D-echo was less in anterior and lateral segments (68 and 48%, respectively) than in inferior and posterior segments (95%). On a per-patient basis, the agreement between the 2 methods was nonetheless high, with only 2 patients with very small infarcts missed by CE-3D-echo.

Because all false-positive segments were located within the septum, we further investigated features of BSAs. We showed that the assessment of both the location and thickening of BSAs allows differentiating normal “septal stripes” from fibrotic septal scars. We observed 2 different patterns. In some patients, these BSAs were located in the middle of the septum, were surrounded by hypoechoic bands, and were significantly thickened on the end-systolic frame. None of these showed DE-cMR enhancement. This pattern, which was prevalent in patients (32%) and controls (30%), probably corresponds to the so-called “septal stripes” and presumably represents the location of the circumferential fibers that run perpendicular to the echo scan plane.\(^2\) In the remaining 18 patients, the BSAs were found in the subendocardium on the end-diastolic frame and were therefore considered myocardial scars in our study. In 9 patients, however, no late enhancement was found on DE-cMR. In each case, these “false-positive” BSAs showed significant systolic thickening and became more midseptal on the end-systolic frame. These BSAs probably correspond to septal stripes as well. Finally, in the last 9 patients, the subendocardial BSAs did not thicken during systole and remained subendocardial on the end-systolic frame. All showed significant delayed enhancement on DE-cMR.

CE-3D-echo also permitted assessment of the transmural extent of scar tissue across the LV wall. Here again, the ability of CE-3D-echo was quite good, with positive and negative predictive values to predict >50% transmural extent by DE-cMR of 91±7% and 98±1%, respectively. Only 16 segments were misclassified by CE-3D-echo. Fourteen of these segments had transmural extents ranging between 45% and 55% by both methods. Their misclassification was thus more related to the dichotomous nature of our analysis rather than to intrinsic inaccuracies in either of the 2 methods. Finally, CE-3D-echo also permitted accurate quantification of the total mass of scar tissue and hence, of infarct size.

<table>
<thead>
<tr>
<th>Scar mass, g</th>
<th>Intraobserver</th>
<th>Interobserver</th>
<th>Test-Retest</th>
<th>Intraobserver</th>
<th>Interobserver</th>
<th>Test-Retest</th>
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<tbody>
<tr>
<td>CE-3D-echo</td>
<td>0.94</td>
<td>0.93</td>
<td>0.95</td>
<td>0.5±2.7</td>
<td>0.0±3.1</td>
<td>−0.9±1.9</td>
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<tr>
<td>DE-cMR</td>
<td>0.95</td>
<td>0.95</td>
<td>0.92</td>
<td>0.2±2.8</td>
<td>−1.3±3.3</td>
<td>−1.4±3.1</td>
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<td>Infarct size, % of LV</td>
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<tr>
<td>CE-3D-echo</td>
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<td>0.94</td>
<td>0.95</td>
<td>0.4±2.2</td>
<td>0.1±2.3</td>
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<td>DE-cMR</td>
<td>0.95</td>
<td>0.95</td>
<td>0.97</td>
<td>0.0±2.4</td>
<td>0.9±2.3</td>
<td>−0.9±1.8</td>
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<td>Transmurality, %</td>
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<tr>
<td>CE-3D-echo</td>
<td>0.93</td>
<td>0.90</td>
<td>0.92</td>
<td>0.2±6.9</td>
<td>0.3±7.7</td>
<td>0.4±6.5</td>
</tr>
<tr>
<td>DE-cMR</td>
<td>0.94</td>
<td>0.94</td>
<td>0.94</td>
<td>0.9±6.6</td>
<td>0.2±7.3</td>
<td>−0.5±5.5</td>
</tr>
</tbody>
</table>

LV indicates left ventricle.

\(^*\)Data are intraclass correlation coefficient.

\(^†\)Data are mean±SD.
Several previous studies have used CE echo to assess myocardial viability.\textsuperscript{2,23} None of them, however, reported on the presence of hyperechoic signals in nonviable segments. Instead, they always identified nonviable myocardium as areas of reduced brightness or contrast intensity, which is just opposite to our findings. These apparently diverging results can readily be explained by the way the contrast echo images were acquired in these different studies. Because in the earlier works, identification of nonviable myocardium relied on the assumption that nonviable segments are hypoperfused and hence, should exhibit reduced signal intensity, the former investigators used contrast-specific imaging modalities, which almost completely suppress the signals emanating from the underlying native tissue. Accordingly, these modalities also eliminated the hyperechoic signals emanating from scar tissue and made nonviable myocardium (presumably scarred) appear darker than normal or viable myocardium.

**Reproducibility of CE-3D-Echo and DE-cMR**

**Assessment of Scar Mass and Scar Transmurality**

Previous studies with 3D-echo to measure LV volumes, LV ejection fraction, and LV mass have shown that this technique was more reproducible than 2D-echo and as reproducible as cMR.\textsuperscript{13–15} The results of our study are thus in line with these previous results. Myocardial scar measurements from CE-3D-echo images are as reproducible as those obtained by DE-cMR (Table 2), a particularly important finding for the follow-up of patients with ischemic heart disease.

**Test-Retest Variation**

In contrast to the more widely reported parameters of intraobserver and interobserver variability, which relate to the repeated measurement of a single dataset, test-retest variation involves repetition of the entire acquisition and analysis. Assessment of test-retest variations is important because imaging factors contribute to variations in infarct size over time. The present study demonstrates that test-retest variations in CE-3D-echo and DE-cMR measurements of scar mass and scar transmurality are quite similar. This is also an important finding because these measurements are often used to help make clinical decisions. Because CE-3D-echo is far more available and less costly than DE-cMR, our findings suggest that CE-3D-echo could become an alternative modality to DE-cMR when DE-cMR is either unavailable or contraindicated.

**Study Limitations**

The present study has limitations that should be acknowledged. First, we did not study the time course of appearance of the hyperechoic signals after myocardial infarction. On the basis of previously published experimental data, which indicated that echo intensity in the infarct zone becomes maximal 6 to 8 weeks after the index event, we only studied patients whose myocardial infarctions were older than 3 months.\textsuperscript{11} Because CE-3D-echo relies on the detection of dense tissue fibrosis, it is unlikely to allow identification of irreversible tissue damage early after acute infarction. At these earlier time points, use of contrast-specific modalities might be better suited, as they specifically interrogate microvascular integrity.\textsuperscript{24} Second, we did not acquire 2D-echo images because 2D imaging is not well suited to display the full 3D extent of the scarring process. Third, scar quantification by the 2 techniques was performed with 2 different software packages. For CE-3D-echo, we used a prototype version of QLab software, which allows precise delineation of endocardial, epicardial, and scar borders on 3D-echo full volumes. For DE-cMR, we used Segment software. Although this software also allows precise delineation of contours on DE-cMR images, contour delineation is performed on consecutive short-axis slices and not on a 3D full volume. The resulting partial-volume effects may lead to overestimation of the scar mass, particularly when it is located at the apex. Forth, the 3D transducer used in this study was quite bulky and sometimes difficult to fit into the intercostal spaces. This resulted in a relatively high rate of dropout artifacts in the anterior and lateral walls, which probably explains the lower sensitivity of CE-3D-echo in these regions. In the future, introduction of 3D transducers with a smaller footprint should help reduce the occurrence of these artifacts and permit better delineation of scar tissue in the anterior and lateral walls. Last, the 3D algorithm used to draw the endocardial, epicardial, and scar contours is not yet fully automated and still requires some manual adjustments. Future development of the software should thus aim at tracking these contours automatically to further improve the robustness of the measurements.

**Conclusions**

CE-3D-echo is a promising new tool for the detection and quantification of myocardial infarct scars. Future developments are nonetheless needed to improve the sensitivity of the technique, particularly in the anterior and lateral walls, where dropout artifacts are common.

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**Disclosures**

None.

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**CLINICAL PERSPECTIVE**

In patients with chronic LV dysfunction, the identification and the quantification of scarred myocardium is important to 
determine the ischemic or nonischemic origin of cardiomyopathies, to determine the patients’ prognosis, and to predict 
functional recovery after revascularization or resynchronization therapy. The aim of this study was to test the hypothesis 
that 3D-Echo can detect and quantify myocardial scars, using delayed-enhanced cardiac magnetic resonance (DE-cMR) as 
the reference standard. The results indicate indeed that CE-3D-Echo allows for the segmental identification of myocardial 
scars with a sensitivity of 78% and a specificity of 99%. Good correlation and limits of agreement were found between 
the assessment of scar mass and transmurality by CE-3D-Echo and DE-cMR. Finally, intraobserver, interobserver and 
test-retest reproducibility was comparable with both techniques. This study demonstrates that CE-3D-Echo is a promising 
alternative to DE-cMR in the field of scar imaging, and opens the way for further research protocols. Future developments 
are nonetheless needed to improve the sensitivity of the technique, particularly in the anterior and lateral walls, where 
attenuation and rib artifacts are common.
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1. **Video-Intensity of pericardium and septal stripe.**

The following figure shows the relationship between mechanical index and videointensity in scar tissue (circles), pericardium (triangles) and septal stripes (squares), for each tested ultrasonic modality.
2. **Septal stripe illustration.**

Representative end-diastolic (left panel) and end-systolic (right panel) CE-3D-Echo 4-chamber view still frames showing thickening of a septal stripe.