3D delayed-enhanced magnetic resonance sequences improve conducting channel delineation prior to ventricular tachycardia ablation

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Received 28 May 2014; accepted after revision 8 October 2014; online publish-ahead-of-print 23 January 2015

Aims
Non-invasive depiction of conducting channels (CCs) is gaining interest for its usefulness in ventricular tachycardia (VT) ablation. The best imaging approach has not been determined. We compared characterization of myocardial scar with late-gadolinium enhancement cardiac magnetic resonance using a navigator-gated 3D sequence (3D-GRE) and conventional 2D imaging using either a single shot inversion recovery steady-state-free-precession (2D-SSFP) or inversion-recovery gradient echo (2D-GRE) sequence.

Methods and results
We included 30 consecutive patients with structural heart disease referred for VT ablation. Preprocedural myocardial characterization was conducted in a 3 T-scanner using 2D-GRE, 2D-SSFP and 3D-GRE sequences, yielding a spatial resolution of 1.4 × 1.4 × 5 mm, 2 × 2 × 5 mm, and 1.4 × 1.4 × 1.4 mm, respectively. The core and border zone (BZ) scar components were quantified using the 60% and 40% threshold of maximum pixel intensity, respectively. A 3D scar reconstruction was obtained for each sequence. An electrophysiologist identified potential CC and compared them with results obtained with the electroanatomic map (EAM). We found no significant differences in the scar core mass between the 2D-GRE, 2D-SSFP, and 3D-GRE sequences (mean 7.48 ± 6.68 vs. 8.26 ± 5.69 and 6.26 ± 4.37 g, respectively, P = 0.084). However, the BZ mass was smaller in the 2D-GRE and 2D-SSFP than in the 3D-GRE sequence (9.22 ± 5.97 and 9.39 ± 6.33 vs. 10.92 ± 5.98 g, respectively; P = 0.042). The matching between the CC observed in the EAM and in 3D-GRE was 79.2%; when comparing the EAM and the 2D-GRE and the 2D-SSFP sequence, the matching decreased to 61.8% and 37.7%, respectively.

Conclusion
3D scar reconstruction using images from 3D-GRE sequence improves the overall delineation of CC prior to VT ablation.

Keywords
Magnetic resonance imaging • Ventricular tachycardia ablation • Conducting channels

Introduction
In recent years, many studies have clearly documented a relationship between several myocardial fibrosis parameters derived from late gadolinium enhancement cardiac magnetic resonance (LGE-CMR) and ventricular arrhythmias occurrence or inducibility.1-5 From a mechanistic point of view, conducting channels (CCs) are considered a probable isthmus of ventricular tachycardia (VT), and substrate ablation techniques consider complete CC elimination critical to achieving non-inducibility of ventricular arrhythmias.6-8 Several studies have demonstrated the utility of LGE-CMR imaging to identify CC using 3D scar reconstructions to characterize the myocardial fibrosis in two types of tissues: the scar core, represented by dense hyperenhanced areas, and the border zone (BZ), reflecting

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What’s new?

- Several studies have demonstrated the capability of late gadolinium enhancement magnetic resonance images (LGE-MRIs) to identify the presence of border zone corridors (channels) in the ventricular scar tissue. These border zone corridors match in a high proportion of cases with conducting channels identified on the electroanatomical maps. This is considered the substrate for the ventricular arrhythmias (VA) and the target for ablation.
- Various different LGE-MRI sequences are capable of identifying this VA substrate. However, no direct comparison has been made between these sequences. It could be important to standardized image acquisition and to optimize VA substrate identification.
- This study demonstrates that 3D sequences provide the best image quality to depict the VA substrate and that this is due to the absence of shifting between consecutive slices but also to the higher spatial resolution as compared with the standard 2D sequences.

Delayed-enhanced CMR protocol

From June 2009 to September 2012, our hospital scheduled 31 patients for LGE-CMR examination. One patient was excluded due to patient intolerance to the long acquisition time of the 3D-GRE sequence. The 3 Tesla scanner (Magnetom Trio a Tim System, Siemens Healthcare) was equipped with 32 independent receiver channels and a 16-channel cardiac coil. The system provides a strength of 45 mT/m, enabling a slew rate of 200 T/m/s. No medications, other than those given for the clinical VT, were administered prior to the study. The patients were instructed to maintain a shallow, steady respiration. An intravenous dose of 0.2 mmol/kg of gadodiamide (Omniscan, Amersham Health) was given, and LGE-CMR imaging was started 7 min later to ensure the correct acquisition of the three sequences. A TI scout was prescribed in a mid-ventricular short-axis view to select the appropriate TI to null healthy myocardium.

First, a whole-heart, high spatial resolution, delayed-enhanced study was conducted using a commercially available free-breathing, 3D-GRE inversion-recovery gradient echo technique as previously described (Gradient echo readout). The 3D slab was acquired in the axial plane. A Cartesian trajectory was used to fill the k-space with phase-encoding (y) in the anteroposterior direction. The field of view was covered by a 256 × 240 pixel matrix, and in-plane reconstruction was allowed to achieve an isotropic spatial resolution of 1.4 × 1.4 × 1.4 mm and a voxel size of 2.74 mm³. To compensate for the long acquisition time anticipated, we added 50 ms to the nominal value necessary to null normal myocardium, as derived from the TI scout. Other typical sequence parameters were as follows: repetition time, 440 ms; echo time, 1.29 ms; flip angle, 15°; bandwidth, 810 Hz/pixel; and 51 k-space lines filled every other heartbeat. In some cases, a high temporal resolution, 4-chamber view cine, achieved by means of parallel imaging with an acceleration factor of 3, was used to select the optimal acquisition window and minimize cardiac motion in late-diastole. Respiratory synchronization was performed for every other heartbeat using a crossed-pair navigator approach. The dataset was acquired during expiration and generalized, autocalibrating, partially parallel acquisition with an acceleration factor of 2 was used to speed up data acquisition. A set of images was reconstructed in the left ventricle (LV) short-axis orientation with 1.4 mm slice thickness (typically 50–70 images) for subsequent image processing. A new TI scout was prescribed to select an updated TI.

Using a well-established, segmented 2D inversion-recovery gradient-echo sequence (2D-GRE), a set of conventional delayed enhanced images was obtained. Consecutive 3 mm thick slices with no gap between them were prescribed to accomplish full LV coverage in the short-axis orientation (one slice per breathhold). Typical parameters were repetition time 790 ms; echo time 2 ms; flip angle, 25°; bandwidth, 140 Hz/pixel; and 35–45 k space lines filled every other heartbeat, needing 10–15 heartbeats per slice. This sequence has been validated for clinical use at 3 T. The mean in-plane resolution was 1.4 × 1.4 mm, and the voxel size was 9.80 mm³.

Finally, a stack of ultra-fast short-axis slices were obtained from the same locations as the 2D-GRE, using a single-shot inversion-recovery 2D-SSFP without phase-sensitive reconstruction. This technique has been validated against 2D-GRE at 1.5 T and 3 T field strength. Basic parameters were as follows: repetition time, 830 ms; echo time, 2.27 ms; flip angle, 50°; and bandwidth, 1240 Hz/pixel. Trigger was set as every other heartbeat. Typically, 26 cardiac cycles were necessary to image 13 slices during one single breathhold. A matrix size of 192 × 192 pixels and a mean field of vision of 380 × 380 mm rendered an in-plane resolution of 2.0 × 2.0 mm and a voxel size of 20.00 mm³.

Methods

Patient sample

As part of our ongoing clinical protocol, patients with ventricular arrhythmia and structural heart disease who are referred for catheter ablation undergo a LGE-CMR examination. Our study consisted in the addition of the 3D-GRE sequence to the clinical LGE-CMR protocol. The local ethics committee approved the study protocol and all included patients signed the informed consent. Patients with implantable devices or other classical contraindications to LGE-CMR, such as clinical instability and claustrophobia, and those referred for VT ablation and arrhythmogenic right ventricular dysplasia were excluded from the study.
epicardial EAM was also obtained. To identify the presence of CC, in the case of epicardial access, an acic epicardial access was performed for epicardial mapping and ablation. For VT or endocardial ablation was unsuccessful, nonsurgical transthoracic mapping. When endocardial mapping did not identify a substrate was introduced through transseptal or retrograde aortic access for endocardial mapping. Using a standard cine SSFP, an electrode irrigated-tip catheter (Thermocool Navistar, Biosense Webster) was introduced through the femoral vein and placed at the RV apex. A 3.5 mm electrode irrigated-tip catheter (Thermocool Navistar, Biosense Webster) was introduced through transeptal or retrograde aortic access for endocardial mapping. When endocardial mapping did not identify a substrate for VT or endocardial ablation was unsuccessful, nonsurgical transthoracic epicardial access was performed for epicardial mapping and ablation.

A CARTO navigation system (Biosense Webster, Diamond Bar) was used to guide the ablation. A tetrapolar diagnostic 6F catheter was introduced through the femoral vein and placed at the RV apex. A 3.5 mm electrode irrigated-tip catheter (Thermocool Navistar, Biosense Webster) was introduced through transeptal or retrograde aortic access for endocardial mapping. When endocardial mapping did not identify a substrate for VT or endocardial ablation was unsuccessful, nonsurgical transthoracic epicardial access was performed for epicardial mapping and ablation.

A high-density LV endocardial substrate EAM was obtained in each case to identify the presence of CC. In the case of epicardial access, an epicardial EAM was also obtained. The point density in the scar regions was also obtained by measuring the scar area in the EAM and counting the total number of points in these areas.

**Myocardial fibrosis quantification**

The myocardial fibrosis region was delimited manually in all short-axis slices by using the segmentation programme TCTK. The myocardial fibrosis tissue was split into core and BZ using an algorithm based on the pixel with the maximum signal intensity (MPI) of the myocardial fibrosis region. Thresholds were calculated between core and BZ as 60% of MPI and between BZ and healthy tissue as 40% of MPI, as previously described. Total core and BZ mass were obtained by multiplying the product of all the voxels for each region by \( m_{\text{voxel}} \) (further details in Supplementary material online Files).

**Identification of conducting channels**

Using an investigational software tool (ADAS, Galgo Medical SL), LV endocardial and epicardial borders were delimited with a semiautomatic segmentation algorithm. A manual adjustment was required to fit the surface to the CMR images. Starting from the LV borders, five concentric layers from the endocardium to epicardium were created (10%, 25%, 50%, 75%, and 90% of the LV wall thickness). After the LV surfaces were obtained, the CMR information was projected over each surface mesh node using a trilinear interpolation, and was colour-coded in order to visualize the signal intensity distribution (see Supplementary material online Files for further details).

Using the same thresholds described previously to differentiate the scar core from the BZ and the BZ from the healthy tissue (starting at 60% and 40% of the MPI, respectively, and using a maximum variation of ± 5%), the colour scale was modified to mimic that used in the EAM.

Shifting between consecutive images was evaluated qualitatively as follows: (1) absent, when no spatial displacement between slices was observed; (2) mild, when shifting between images was present but did not compromise the segmentation; (3) moderate, when image shifting caused inadequate segmentation in any region; and (4) severe, when image shifting impeded correct 3D reconstruction of the LV.

All CCs were identified both in the LGE-CMR reconstructions and EAM. A CC in the LGE-CMR reconstruction was defined as a corridor of BZ between two core areas or between a core area and a valve annulus, whether observed in the same layer or between consecutive layers.

An electrophysiologist, masked to the EAM data, analysed the 3D reconstructions and identified the CC according to their distribution across the whole LV wall thickness. If the image quality of any set of images was too low to be reconstructed (the presence of artefacts or severe slice-shifting effects) the set was considered unreadable. Another electrophysiologist blinded to the LGE-CMR reconstructions labelled the presence of CC in the EAM. The CC in the EAM was defined as voltage CC and late-potential (LP) CC, following the same criteria defined in a previous study.

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An example is shown in the Supplementary material online Files. After that, both readings were compared side by side by the two electrophysiologists and they determined the matching between CC observed in the EAM and those observed in the LGE-CMR reconstructions (see Figure 2). A third independent observer assessed the agreement between LGE-CMR and EAM in CC depiction in case of disagreement. In cases where only endocardial EAM were available, the CC identified in the epicardial LGE-CMR 3D reconstructions (layers 75% and 90%) were not taken into account in the final analysis.

**Statistical analysis**

Quantitative variables are expressed as mean value ± standard deviation and qualitative variables as number and percentage. Comparisons between the different sequences were made using paired t-test and the

**Figure 1** View of a representative slice of the same patient obtained by the 2D-GRE sequence (A), the 2D-SSFP sequence (B), and the 3D-GRE sequence (C).
repeated-measures analysis of variance test. The intra-observer agreement and inter-observer agreement were assessed using Lin’s coefficient. Statistical significance was set at $P < 0.05$. All data were analysed using the PASW Statistics 18.0 software (SPSS Inc).

Results
A total of 23 (76.7%) patients with ischaemic cardiomyopathy and 7 (23.3%) patients with non-ischaemic cardiomyopathy were included in the study. Twenty-four (80.0%) patients were referred for VT ablation and 6 (20.0%) patients were referred for scar-related premature ventricular contractions ablation. Patient characteristics are shown in Table 1.

Delayed-enhanced cardiac magnetic resonance results
The LGE-CMR study was performed a mean of 6.4 ± 10.7 days prior to the VT ablation procedure. The mean acquisition time of the whole scan was 89.60 ± 16.54 min (including the administration of gadolinium). The mean acquisition time was 11.64 ± 4.28 min for the 2D-GRE sequence and 1.06 ± 0.64 min and 16.43 ± 7.19 min for 2D-SSFP and 3D-GRE, respectively ($P < 0.001$). As expected, the number of short-axis images available for analysis was higher with the 3D-GRE sequence. Accordingly, the time required for LV segmentation was higher with the 3D-GRE compared with the others (Table 2).

There were no differences in total myocardial fibrosis mass between the different LGE-CMR sequences. No significant differences were observed in the core mass images obtained with 3D-GRE as compared with the standard 2D-GRE sequence, but there was a small difference ($P = 0.007$) as compared with the 2D-SSFP sequence. No differences were found in the total core mass between the 2D-GRE and 2D-SSFP images. In line with these results, the 8Z mass was higher in the 3D-GRE than in the 2D-GRE and the 2D-SSFP sequences. More details are shown in Table 2.

The intra-observer agreement showed a good matching between the different measures (Lin’s coefficient was $>0.9$ in all cases). See Supplementary material online Table S1 for further details.
In four (13.3%) cases, the 2D-GRE sequence had severe shifting and 3D reconstruction could not be performed. In five (16.7%) cases, moderate shifting was observed. With regard to the 2D-SSFP sequence, moderate shifting was observed in five (16.7%) studies with no cases of severe displacement. One patient (3.2%) was excluded because the 3D-GRE sequence was not completed due to claustrophobia.

Conducting channel analysis
A total of 30 endocardial EAMs and 9 epicardial EAMs were obtained. The mean number of points for the endocardial and epicardial EAMs was 422.6 ± 194.1 and 475.0 ± 242.7, respectively. The mean point density in the scar areas was 7.45 ± 2.84 points/cm². The overall number of CC identified in the EAM was 77 (mean 2.55 ± 1.64). A total of 74 CCs (mean 2.47 ± 1.25) were identified in the 3D-GRE dataset, whereas only 54 CCs (mean 2.08 ± 1.26) and 37 CCs (mean 1.23 ± 0.97) were depicted using the 2D-GRE and 2D-SSFP, respectively. The agreement (or sensibility) between the CC present in the EAM and those identified in the 3D LV reconstructions using the 2D-GRE, 2D-SSFP, and 3D-GRE sequences were 61.8%, 37.7%, and 79.2%, respectively (see Figure 3). The analysis of the 2D-GRE was made taking only into account the cases where the 3D reconstruction using the images provided by this sequence was possible.

Data on baseline VT isthmus identification cannot be provided, as the four-step ablation protocol in our centre (mapping, substrate ablation, re-mapping, and the induction and ablation of residual inducible VT if any) does not include a VT induction attempt before ablation. We identified 24 VT isthmuses, most of them residual inducible VTs for which the VT isthmus was identified during the re-map after substrate ablation. These VT isthmuses were also identified in the 3D LV reconstructions in 15 (68.2%) VT cases when the 2D-GRE sequence was used, 7 (29.2%) VT cases using the 2D-SSFP sequence, and 21 (87.5%) cases using the 3D-GRE sequence.

### Discussion
Characterization of fibrotic tissue with LGE-CMR is widely performed using conventional imaging based on breathhold segmented inversion recovery gradient echo or rapid SSFP techniques validated for diagnosis and viability evaluation in multiple clinical scenarios. However, imaging at a higher spatial resolution is becoming imperative in the field of arrhythmias, where a higher level of detail is mandatory to plan ablation strategy and technique. This study shows that imaging with a free-breathing 3D acquisition at 3 T field strength is superior to conventional LGE-CMR techniques to depict CC among patients referred for ventricular arrhythmia ablation. This higher capacity of the 3D-GRE sequence to detect the arrhythmogenic substrate could be used for better sudden cardiac death risk stratification and to better guide and plan ablation procedures.

The unique ability of cardiac LGE-CMR to depict fibrotic myocardium with unprecedented precision makes the technique particularly attractive in the field of arrhythmias. From the very beginning, even coarse features reflecting myocardial fibrosis morphology on conventional 2D LGE-CMR images, such as infarct mass or infarct surface area, have been identified as predictors of ventricular arrhythmia inducibility. Later on, a more refined approach to characterize the myocardial fibrosis components into a dense core or an heterogeneous mixture of viable and patchy fibrotic myocardium, called border zone, proved to be a stronger predictor of cardiac mortality and ventricular arrhythmia inducibility than infarct sizing. In addition, several experimental studies have demonstrated distinctive electrophysiological conduction properties of myocardial tissue according to their characterization using high-resolution LGE-CMR.

### Table 1 Patient demographics

<table>
<thead>
<tr>
<th>Demographic data</th>
<th>N = 30</th>
</tr>
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<tbody>
<tr>
<td>Age (years)</td>
<td>65.6 ± 9.3</td>
</tr>
<tr>
<td>Men</td>
<td>27 (90.0%)</td>
</tr>
<tr>
<td>Hypertension</td>
<td>23 (76.7%)</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>5 (16.7%)</td>
</tr>
<tr>
<td>Dyslipidemia</td>
<td>24 (80.0%)</td>
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<tr>
<td>Cardiac magnetic resonance data</td>
<td></td>
</tr>
<tr>
<td>LV ejection fraction (%)</td>
<td>30.3 ± 10.9</td>
</tr>
<tr>
<td>LV end-diastolic volume (mL)</td>
<td>220.7 ± 88.3</td>
</tr>
<tr>
<td>LV end-systolic volume (mL)</td>
<td>159.1 ± 79.9</td>
</tr>
<tr>
<td>LV mass (g)</td>
<td>125.9 ± 32.3</td>
</tr>
<tr>
<td>Antiarrhythmia treatment</td>
<td></td>
</tr>
<tr>
<td>Beta blockers</td>
<td>20 (66.7%)</td>
</tr>
<tr>
<td>Amiodarone</td>
<td>9 (30.0%)</td>
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</table>

### Table 2 Comparison between the three sequences studied

<table>
<thead>
<tr>
<th></th>
<th>2D-GRE</th>
<th>2D-SSFP</th>
<th>3D-GRE</th>
<th>2D-GRE vs. 2D-SSFP (P value)</th>
<th>2D-GRE vs. 3D-GRE (P value)</th>
<th>2D-SSFP vs. 3D-GRE (P value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Myocardial fibrosis mass (g)</td>
<td>16.70 ± 10.89</td>
<td>17.65 ± 10.70</td>
<td>17.18 ± 9.32</td>
<td>P = 0.168</td>
<td>P = 0.689</td>
<td>P = 0.641</td>
</tr>
<tr>
<td>Core mass (g)</td>
<td>7.48 ± 6.68</td>
<td>8.26 ± 5.69</td>
<td>6.26 ± 4.37</td>
<td>P = 0.280</td>
<td>P = 0.522</td>
<td>P = 0.007</td>
</tr>
<tr>
<td>BZ mass (g)</td>
<td>9.22 ± 5.97</td>
<td>9.39 ± 6.33</td>
<td>10.92 ± 5.98</td>
<td>P = 0.815</td>
<td>P = 0.028</td>
<td>P = 0.040</td>
</tr>
<tr>
<td>Acquisition time (min)</td>
<td>11.64 ± 4.28</td>
<td>10.6 ± 0.64</td>
<td>16.43 ± 7.19</td>
<td>P &lt; 0.001</td>
<td>P = 0.008</td>
<td>P &lt; 0.001</td>
</tr>
<tr>
<td>Segmentation and processing time (min)</td>
<td>1.85 ± 0.38</td>
<td>1.70 ± 0.42</td>
<td>9.01 ± 2.83</td>
<td>P = 0.002</td>
<td>P &lt; 0.001</td>
<td>P &lt; 0.001</td>
</tr>
</tbody>
</table>
imaging, which opens the possibility for the technique to become a clinical tool for preprocedural planning of VT ablation. Ashikaga and coworkers showed that LGE-CMR with submillimetre resolution is able to reveal the isthmus of the reentry circuits critical for VT generation as areas of complex 3D disarrayed mixture of viable and fibrotic tissue. Their study used postmortem cardiac imaging, in which cardiac and respiratory motion was not at play, and acquisition time limitations were not an issue. Since then, a great interest in developing fast, high-resolution imaging techniques has evolved into the development of clinical scenarios that overcome the inherent limitations of in vivo imaging.

So far, the accumulated evidence suggests that areas with intermediate grades of viable tissue within the scar are the substrate for slow conduction channels. These areas can be depicted by LGE-CMR, although the equipment and sequences used, as well as the spatial and temporal resolution achieved, affect the imaging results. In this regard, imaging with sufficient spatial resolution remains a critical issue. Previous work demonstrated that the amount of myocardium defined as BZ within the myocardial fibrosis varies substantially depending on the spatial resolution achieved. Using delayed-enhancement imaging in a murine model at high field strength, Schelbert and co-workers observed an excellent correlation between the gadolinium deposition and the histological pattern of fibrosis distribution nearly at the cellular level. Interestingly, when image resolution was degraded to resemble the clinical situation, the BZ increased but total infarct size remained unchanged. The authors claimed that partial volume effects accounted for the increase when image resolution was pushed down. In line with these results and those obtained in other studies where comparison in scar quantification between 2D and 3D sequences was performed, our study did not find significant differences in total infarct size with the 3D and 2D sequences. However, despite a higher spatial resolution with the 3D-GRE technique, we found that BZ was significantly larger with the 3D-GRE sequence than with the 2D sequences, a finding that cannot be explained by an increase in partial volume effect. This might have accounted for an increase in the amount of tissue showing intermediate signal intensity, finally classified as BZ.

Conducting channels delineation

Correct CC visualization using LGE-CMR images before the ablation procedure can be a useful tool to plan and guide the intervention. Nevertheless, different LGE-CMR sequences were described in each of those studies. 2D-GRE sequences present the problem of displacement between slices due to respiratory motion that limits a correct 3D reconstruction of the LV. In this study, 30% of the cases had severe or moderate displacement between slices that impeded a correct 3D reconstruction. 2D-SSFP theoretically corrects this undesirable effect by making the full acquisition in a single breathhold. However, in our study 16.7% of cases have moderate displacement between images, probably as the result of the need of an excessively long breathhold. The effect of displacement between consecutive slices of a set of images may result in critical errors in the 3D reconstructions of the LV surface. If a slice registration method to correct the displacement is not applied to the set of images, erroneous projection of CMR information over the 3D LV reconstructions could lead to incorrect interpretation of the data.

The 3D LV reconstructions using the 3D-GRE sequences provided the highest number of CC also observed in the EAM. The percentage of CC identified both in the EAM and in the 3D LV reconstruction was similar to that reported in previous studies. This can be explained by the higher spatial resolution of this sequence, which facilitates the depiction of CC in the 3D LV reconstruction. For the same reason,
2D-SSFP provided the lowest sensitivity in identifying CC. The percentage of false positives (~20%) was very similar in the three sequences.

The results from this study support that the higher sensitivity in CC detection is obtained at the cost of longer acquisition and processing times, especially with the 3D-GRE sequence. The 2D-GRE sequence could provide an alternative because of its capability to identify up to 60% of CC with lower acquisition and processing times. In those cases in which the acquisition time of 3D-GRE and even 2D-GRE could be problematic (e.g. claustrophobia, breathing-related difficulties), the 2D-SSFP sequence could be a useful alternative, although the sensitivity of this sequence is modest.

In some cases, the length/width of the CC identified was close to the spatial resolution of the sequence because the 3D LV reconstructions were used for observation of CC, rather than the raw CMR images. The trilinear interpolation applied to the LV surface nodes made this possible, smoothing the transition between the different SI of the voxels over the LV reconstruction and sometimes showing CC with a length close to the spatial resolution of the CMR sequence (see Figure 4). In addition, a previous study described the capability of a 2D sequence similar to that used in this study and with the same spatial resolution to identify CC related to VT isthms.22 In that study, 100% of the CCs identified in the EAM were observed in the LGE-CMR images. The reason for the mismatch between that study and our results was mainly due to differences in methodology. All CCs identified in the EAM by Pérez-David et al. were voltage CCs, whereas in our study both voltage and LP CCs were considered for the comparative analysis.

Although most of the CCs observed in the EAM can be identified using the 3D-GRE sequence, nearly 20% of CCs still not visible in the 3D LV reconstructions. Higher LGE-CMR spatial resolution could improve the identification capacity.

3 T scans provide a higher signal level, reducing time scans and/or improving the quality of the images obtained by means of reducing the voxel size. This theoretically results in an increased number of CCs identified in the CMR images. However, as these CMR studies were not also done in a 1.5 T scan, we do not have data to support this statement. Nevertheless, the sequences described can be performed in a 1.5 T scan, although the results of CC depiction might be different.

Point density in the EAM is critical to obtain detailed information of the tissue. Sometimes certain areas of the LV are poorly mapped and this may result in losing important information about the presence/absence of CC. In fact, this may be critical for the ablation success. In this context, the CMR could not only correlate with the EAM, but also to show additional tissue details to the EAM. This is why a perfect match should probably not be pursued as the endpoint, but an acceptable similarity.

Limitations

Our study has several limitations. In 3.2% of the cases, the 3D-GRE could not be completed due to respiratory motion or excessively long acquisition time. Factors related to patient cooperation and arrhythmia may increase substantially the acquisition time, which ends up limiting image quality and the clinical applicability of the technique. In addition, we did not test other validated methods for classifying BZ, such as the standard deviation approach. In a recent study, the BZ
defining the standard deviation method was superior to that achieved with methods proposed by Yan and Schmidt to predict VT inducibility. Nonetheless, we used the method that in our hands has provided a better correlation compared with the EAM in previous studies. Another limitation of the study is the comparison of the CCs identified in the EAM and those observed in the LGE-CMR. A side-by-side comparison may be subjective despite the presence of a third observer to solve disagreements. Besides, resolution of EAM may be sometimes not enough to identify all the CC.

Conclusions

3D scar reconstruction using images from 3D-GRE sequence improves the overall delineation of CCs prior to VT ablation.

Supplementary material

Supplementary material is available at Europace online.

Acknowledgements

We are indebted to the Medical Imaging core facility of the IDIBAPS for technical assistance. We thank Luis Lasalvia, MD, MIB; Okan Ekinci MD, MBA and Andreas Greiser, PhD for their great support and collaboration.

Conflict of interest: David Andreu is employed by Biosense Webster.

Funding

This study was partially supported by a grant from the ‘Fondo de Investigación Sanitaria’ (FIS 2012–2014, PI11/02049). This study has been supported by Siemens Healthcare and performed in collaboration with the Clinical Competence Center Cardiology, Erlangen, Germany.

References