Usefulness of contrast-enhanced cardiac magnetic resonance in identifying the ventricular arrhythmia substrate and the approach needed for ablation

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Aims
The endocardial vs. epicardial origin of ventricular arrhythmia (VA) can be inferred from detailed electrocardiogram (ECG) analysis. However, despite its clinical usefulness, ECG has limitations. Alternatively, scarred tissue sustaining VAs can be identified by contrast-enhanced cardiac magnetic resonance (ce-CMR). The objective of this study was to determine the clinical value of analysing the presence and distribution pattern of scarred tissue in the ventricles to identify the VA site of origin and the ablation approach required.

Methods and results
A ce-CMR study was carried out before the index ablation procedure in a cohort of 80 patients with non-idiopathic VA. Hyper-enhancement (HE) in each ventricular segment was coded as absent, subendocardial, transmural, mid-myocardial, or epicardial. The endocardial or epicardial VA site of origin was also assigned according to the approach needed for ablation. The clinical VA was successfully ablated in 77 (96.3%) patients, all of them showing HE on ce-CMR. In segments with successful ablation of the clinical ventricular tachycardia, HE was absent in 3 (3.9%) patients, subendocardial in 19 (24.7%), transmural in 36 (46.7%), mid-myocardial in 8 (10.4%), and subepicardial in 11 (14.3%) patients. Epicardial ablation of the index VA was necessary in 3 (6.1%) ischaemic and 12 (42.9%) non-ischaemic patients. The presence of subepicardial HE in the successful ablation segment had 84.6% sensitivity and 100% specificity in predicting an epicardial origin of the VA.

Conclusion
Contrast-enhanced cardiac magnetic resonance is helpful to localize the target ablation substrate of non-idiopathic VA and also to plan the approach needed, especially in non-ischaemic patients.

Keywords
Magnetic resonance • Ventricular tachycardia • Epicardial ablation

Introduction
The combination of endocardial and epicardial mapping and ablation can increase the effectiveness of ventricular tachycardia (VT) ablation procedures in some patients.1–4 However, it remains unclear whether a combined, sequential, or isolated epicardial approach should be the first choice in most of the patients. Although an epicardial approach is mostly recommended after a failed endocardial ablation, intra-procedural anticoagulation therapy increases the risk of complications from a second attempt.5 Any source of data providing useful information on the approach required could help us to plan the initial procedure and avoid complications.

Although electrocardiogram (ECG) analysis during VT is useful to anticipate epicardial origin,6–8 the defined ECG criteria are imperfect and somewhat limited by varying sensitivities and specificities, depending on the substrate and area of origin of the ventricular arrhythmia (VA). In addition, ECG analysis cannot be done in fast VTs or when the 12-lead surface ECG is not available.

Critical anatomical substrates such as scarred tissue support re-entry circuits for endocardial and epicardial VAs.9 Contrast-enhanced cardiac magnetic resonance (ce-CMR) has demonstrated its ability to identify this viable tissue in the scar in vivo with unusual precision in ischaemic and non-ischaemic cardiomyopathies.10–12
We hypothesized that the distribution pattern of the scarred tissue across the ventricle wall thickness can be useful in differentiating between endocardial and epicardial VA. The main objective of the study was to evaluate the usefulness of the ce-CMR alone or in combination with the ECG-suggested ventricular segment of origin (SOO) as a predictor of endocardial vs. epicardial origin.

Methods

Patient sample

Patients with a documented VA in a 12-lead surface ECG submitted for ablation and who underwent ce-CMR before the index procedure were included in the study. Patients without 12-lead ECG of the clinical VA [arrhythmia recorded by the implantable cardioverter defibrillator (ICD) or observed in a 24-h Holter] and an induced VA in the index procedure matching the cycle length of the clinical VA were also included. Patients were considered for VA ablation if they met one of the following criteria: (i) an incessant VT, (ii) repetitive episodes of sustained monomorphic VT, or (iii) symptomatic frequent premature ventricular contractions (PVCs) despite the use of antiarrhythmic drugs, associated with structural heart disease (SHD). Patients with claustrophobia or classical contraindication for a ce-CMR acquisition were excluded. Patients with idiopathic VA not associated with SHD or with the diagnosis of arrhythmogenic right ventricular dysplasia (ARVD) were also excluded. All participants signed their informed consent, and the study protocol was approved by the local Ethics Committee.

Contrast-enhanced cardiac magnetic resonance analysis

Patient-identifying data were removed from ce-CMR images for the analysis, performed by two-independent cardiologists also blinded to any clinical and electrophysiological data. In a case of discordance, a third observer was required. The ce-CMR images were analysed to depict the presence of scarred tissue for each left ventricle (LV) segment according to the 17-segment model. The right ventricle (RV) septum was divided into three segments: right ventricular outflow tract (RVOT), right ventricular inflow tract (RVIT), and right ventricular apex. Equivalence to the 17-segments model of the RV septum was as follows: RVOT—Segment 2; RV apex—Segments 8, 9, and 14; mid-myocardial hyper-enhancement affects Segments 2 (red arrow) and 3. Segment 4 is partially affected. (D) Epicardial hyper-enhancement. Red arrows show epicardial hyper-enhancement in Segments 10 and 11. In these images, it is also possible to observe mid-myocardial hyper-enhancement in Segments 7 and 8.
RVIT—Segment 3. The RV free wall was not taken into account for the analysis, because it was too thin in the spatial resolution of the ce-CMR images to reliably establish a degree of hyper-enhancement (HE) transmurality. For details of the ce-CMR sequence, see Supplementary material online.

Accordingly, the HE pattern distribution for each segment was defined as follows:

- **Endocardial ce-CMR pattern**: HE involved the endocardium with a mean transmural extent ≤ 50% of wall thickness.
- **Transmural ce-CMR pattern**: HE involved the endocardium with a mean transmural extent > 50% of wall thickness.
- **Epicardial ce-CMR pattern**: HE involved the epicardial layer with a mean transmural extent < 50% of wall thickness.
- **Mid-myocardial ce-CMR pattern**: HE extended to < 50% of wall thickness with mid-myocardial distribution.
- **Absence**: No HE was identified in the corresponding segment.

Figure 1 shows examples for each of the five HE types. Sensitivity and specificity analyses were performed both for the presence of one or more segments with epicardial HE and for a predominance of epicardial HE in the ce-CMR images.

**Electrophysiological study**

All participants underwent an electrophysiology study in a fasting state, with oral sedation (10 mg diazepam). Intravenous conscious sedation was used during the electrophysiology study, except in cases of PVC ablation. In PVC cases, ventricular mapping was performed without intravenous sedation and a bolus of fentanyl was administered intravenously before radiofrequency (RF) ablation. A navigation system (CARTO system, Biosense Webster, Diamond Bar, CA, USA) was used to guide the VA ablation. A tetrapolar diagnostic 6-Fr catheter was introduced through the femoral vein and placed at the RV apex. The basal and post-ablation stimulation protocol consisted of programmed ventricular stimulation from the RV apex at three drive cycle lengths with up to three extrastimuli and incremental burst pacing at a cycle length up to 200 ms. If the clinical VT was not inducible, intravenous isoproterenol was used. A 3.5 mm electrode irrigated-tip catheter (Thermocool Navistar, Biosense Webster) was introduced through transseptal or retrograde aortic access for LV endocardial mapping. A non-surgical transthoracic epicardial access was performed for epicardial mapping and ablation when endocardial VT ablation was unsuccessful, when the endocardial mapping did not identify a VT substrate, when the patient had a non-ischaemic cardiomyopathy and the ECG was suggestive of an epicardial origin (before endocardial mapping), or when ce-CMR showed an epicardial scar.

**ECG-suggested ventricular segment of origin**

As scar is usually present in more than one segment and could have different distribution patterns in each one of them, the ventricular segment related to the VA was estimated on the basis of ECG morphology of VT using the Miller classical algorithm. The 17-segment model used for the image analysis and location of the VA origin was adapted to the classical electrophysiology region model (Figure 2).

However, the Miller algorithm applies only to ischaemic patients and there is no validated algorithm to identify the origin of VA in non-ischaemic patients. Therefore, the sensitivity and specificity analyses in predicting an epicardial origin of the VA were performed only for the successful ablation segment.

**Radiofrequency ablation**

Radiofrequency delivery was temperature-controlled with a power limit of 50 W at a target temperature of 45°C at the endocardium. At the epicardium, the ablation settings were 40 W/45°C, and occasionally the power was increased to 50 W. The flow rate was 0 and 17 mL/min during mapping and RF ablation, respectively. Ablation of sustained VT was guided by the identification of diastolic electrograms and entrainment mapping criteria. In the case of unmappable VT, pacemap manoeuvres identified the exit site in the scar and a substrate mapping and ablation approach was performed. In 39 (48.8%) patients, a substrate

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**Figure 2** Adaptation of the electrophysiological 12-segment model to the 17-segment model. Adaptation of the 17-segment model to the anatomical regions described by Miller et al. As a limitation of this algorithm, an important number of regions were not identified as a possible ventricular arrhythmia site of origin.
Ablation was performed in addition to the clinical VT ablation. The same manoeuvres were used for both endocardial and epicardial ablation of the clinical VA. The endpoint of the ablation procedure was the suppression of clinical VA inducibility and of any monomorphic VT, whatever the approach needed. The actual SOO of the clinical VA was determined by the location of the successful ablation site for that VA and was recorded in the CARTO electroanatomical map.

The follow-up was performed every 6 months after the ablation. The visit included clinical evaluation, a 24-h Holter, and an echocardiogram. The definition of PVC recurrence was > 5% of PVC burden in repeated 24-h Holter monitoring (1, 6, and 12 months), and of VT recurrence as any VT episode requiring ICD intervention or documented by any means.

**Mid-myocardial hyper-enhancement analysis**

Patients with mid-myocardial HE in the successful ablation site were analysed in more detail. The distance was measured between the border/centre of the HE and the endo-/epicardium in the case of an LV free wall or between the border/centre of the HE and the endocardial RV and LV surface in a case of a septal scar. This measurement refers to the thickness of the healthy myocardium interposed between the scar and the tip of the ablation catheter at the target ablation site. These patients were excluded from the general sensitivity and specificity analyses of the scar distribution pattern to predict the epicardial origin.

**Statistical analysis**

Quantitative variables are expressed as mean value ± SD, and qualitative variables are expressed as the number and percentage. The sensitivity and specificity, as well as the positive predictive value (PPV) and negative predictive value (NPV), were obtained for the following: (i) the presence of any segment with epicardial HE, (ii) a majority of segments with epicardial HE, and (iii) the type of HE in the successful ablation segment. Comparisons were made using the two-sided χ² test or the Wilcoxon test as appropriate. Statistical significance was set at P < 0.05. All data were analysed using the PASW Statistics 18.0 software (SPSS, Inc., Chicago, IL, USA).

**Results**

Between June 2007 and September 2012, 280 patients underwent an VA ablation procedure in our centre. Of these, 99 patients were referred for idiopathic VT/PVCs and 17 had ARVD. Of the remaining 164 patients, 57 had a previous implantable device (ICD in most of the cases). Twenty-seven patients did not have a previous ce-CMR study, due to logistic or technical reasons or contraindication. The remaining 80 patients were included in the study. Sixty-six (82.5%) patients were referred with a documented sustained VT and 14 (17.5%) with PVCs related to SHD. Fifty-one (63.8%) patients had ischaemic cardiomyopathy, and 39 (36.2%) had non-ischaemic cardiomyopathy. The mean LV ejection fraction was 41.9 ± 12.8%. Patient demographics are summarized in Table 1.

**ECG and electrophysiology study data**

Forty-six (57.5%) patients had a right bundle branch-like VA morphology, whereas 34 (42.5%) had a left bundle branch block (LBBB)-like configuration. In 3 (3.8%) patients, the ablation was unsuccessful, and therefore, the VA SOO was considered indeterminate. In 62 (80.5%) of the remaining 77 patients, the successful ablation was performed endocardially and in 15 (19.5%), those performed epicardially. In patients needing an epicardial ablation, a previous endocardial ablation was unsuccessful in 7 (46.7%) patients and endocardial mapping had been performed in 8 (53.3%). After ablation, non-inducibility of any VA was obtained in 63 (81.8%) patients, and in 14 (18.2%) patients, other non-clinical VA was inducible. The mean number of monomorphic VT induced in the electrophysiological study was 1.56 ± 0.82. If PVC ablation procedures are excluded, the mean number of sustained monomorphic VT increases to 1.63 ± 0.86.

During a median follow-up of 22 (12 – 37) months, 57 of 77 (74.0%) patients with a successful ablation of the clinical VA (and additional substrate ablation in 52.6% of them) were arrhythmia-free. Seventeen (22.1%) patients had VA recurrence. Three (3.9%) patients were lost to follow-up. Most of the patients with a successful PVC ablation (12 of 13, 92.3%) were arrhythmia-free during the follow-up, while 45 of 61 (73.8%) patients with a successful VT ablation had no recurrences.

In the 49 patients with ischaemic heart disease, the successful ablation site of the clinical VT was located at the endocardium in 46 (93.9%) patients, and an epicardial ablation was required only in 3 (6.1%) patients. Non-ischaemic patients more frequently required epicardial ablation (12 (42.9%) patients, P < 0.001; see Table 2 for details).

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Patient demographics (n = 80)</th>
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<tr>
<td><strong>Demographic data</strong></td>
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<tr>
<td>Age (years)</td>
<td>63.5 ± 12.3</td>
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<tr>
<td>Men</td>
<td>77 (96.3%)</td>
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<tr>
<td>Hypertension</td>
<td>54 (67.5%)</td>
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<td>Diabetes mellitus</td>
<td>14 (17.5%)</td>
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<tr>
<td>Hyperlipidaemia</td>
<td>48 (60.0%)</td>
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<tr>
<td>Clinical arrhythmia with LBBB ECG morphology</td>
<td>34 (42.5%)</td>
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<tr>
<th><strong>Echocardiography data</strong></th>
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<tr>
<td>LV ejection fraction (%)</td>
<td>41.9 ± 12.8</td>
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<tr>
<td>LV end-diastolic diameter (mm)</td>
<td>61.3 ± 8.2</td>
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<td>LV end-systolic diameter (mm)</td>
<td>45.3 ± 10.9</td>
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<th><strong>Cardiac magnetic resonance data</strong></th>
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<tr>
<td>LV ejection fraction (%)</td>
<td>36.8 ± 12.7</td>
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<tr>
<td>LV end-diastolic volume (mL)</td>
<td>216.8 ± 69.0</td>
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<tr>
<td>LV end-systolic volume (mL)</td>
<td>142.0 ± 66.0</td>
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<th><strong>Structural heart disease</strong></th>
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<tr>
<td>Ischaemic</td>
<td>51 (63.8%)</td>
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<tr>
<td>Non-ischaemic</td>
<td>29 (36.2%)</td>
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The values are presented as mean ± SD or n (%).

<table>
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<tr>
<th>Table 2</th>
<th>Comparison between the endocardial and epicardial site of successful ablation and the type of structural heart disease (n = 77)</th>
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<tr>
<td><strong>Endocardial successful ablation, n (%)</strong></td>
<td><strong>Epicardial successful ablation, n (%)</strong></td>
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<tr>
<td>Ischaemic</td>
<td>46 (93.9%)</td>
</tr>
<tr>
<td>Non-ischaemic</td>
<td>16 (57.1%)</td>
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Of the 49 patients with ischaemic cardiomyopathy and successful ablation, 3 (6.1%) had a septal scar, 9 (18.4%) an anterior scar, and 37 (75.5%) an inferior scar. Using the Miller algorithm to localize the VT SOO, the ECG-suggested SOO matched with the successful ablation segment in 37 of 49 (75.5%) ischaemic patients. In 3 (6.1%) patients, the algorithm was not applicable because they had a septal infarction. In the remaining 9 (18.4%) patients, the ECG-suggested SOO did not match the successful ablation segment. Of these, 3 (6.1%) patients had scar-related PVC that originated in a papillary muscle, in 5 (10.2%) the successful ablation segment was different from the segment suggested by the ECG, and in the remaining patient (2.1%) the VA originated in a mid-myocardial scar probably caused by hypertensive cardiomyopathy, far away from the infarction scar. Figure 3 shows an example in which the ECG-suggested SOO matched with the successful ablation segment.

Of the 28 non-ischaemic patients, 6 (21.4%) presented endocardial HE, 6 (21.4%) presented transmural HE, 4 (14.3%) presented mid-myocardial HE, and 1 (3.6%) had no HE. All except one patient with mid-myocardial HE had a successful endocardial ablation. In this patient, the successful ablation site was located in the epicardium. On the other hand, 11 (39.3%) patients presented epicardial

Figure 3 Example of the identification of the origin of ventricular arrhythmias using electrocardiogram (ECG) information. Ischaemic patient with anterior infarction. (A) ECG of the ventricular tachycardia. The origin of this ventricular tachycardia is located in the inferoapical septum (Segment 14 in the 17-segment model), according to the Miller algorithm (anterior infarction, left bundle branch block, left superior axis, and late progression of R-wave precordial pattern). (B) Baseline contrast-enhanced cardiac magnetic resonance short-axis image of the same patient. The white arrow identifies an endocardial hyper-enhancement in the inferoapical septum. (C) Activation map during the ventricular tachycardia (right anterior oblique view). It is possible to identify the ventricular tachycardia exit site from the scar in the inferoapical septum. Ablation at this point terminated the ventricular tachycardia.
HE in the SOO. In all of them, the successful ablation site was on the epicardium.

**Contrast-enhanced cardiac magnetic resonance analysis**

The third reviewer was needed in 5 (6.25%) patients. The reasons were: the LV segment assignment for the presence of HE in 1 (1.25%) patients and the HE pattern distribution as transmural or endocardial in 4 (5.0%). In all the patients, HE was observed in some segment, and the median number of segments with HE was 5 (inter-quartile range: 3–8). Only 3 (3.8%) patients with HE had a successful ablation site in a segment without HE. In these three cases, the reason for ablation was frequent PVCs.

The presence of epicardial HE in one or more segments had a sensitivity of 80.0% and a specificity of 88.7% in identifying the epicardial origin of the VA. The PPV was 63.2% and the NPV was 94.8%. When patients were classified as having a predominant epicardial HE pattern (i.e. the number of segments with epicardial HE ≥ number of segments with other HE patterns), the sensitivity decreased to 66.7% but the specificity slightly increased to 98.4%. In this case, the PPV was 90.9% and the NPV was 92.4%.

**Contrast-enhanced cardiac magnetic resonance analysis in combination with electrocardiographic data**

In the subgroup of ischaemic patients to whom the Miller algorithm applies (n = 49) and the algorithm successfully identified the SOO (n = 37), a successful endocardial ablation (n = 34) was associated with subendocardial HE in 6 (17.6%) patients, transmural HE in 26 (76.5%), and absence of HE in 2 (5.9%). On the other hand, a successful epicardial ablation (n = 3) was associated with transmural HE in 2 (66.7%) patients and mid-myocardial HE in 1 (33.3%).

**Contrast-enhanced cardiac magnetic resonance analysis in the successful ablation segment**

Successful endocardial ablation (n = 62) was associated with subendocardial HE in 19 (30.7%) patients, transmural HE in 34 (54.8%), mid-myocardial HE in 6 (9.7%), and absence of HE in 3 (4.8%). Successful epicardial ablation (n = 15) was associated with subepicardial HE in 11 (73.4%) patients, transmural HE in 2 (13.3%), and mid-myocardial HE in 2 (13.3%). In this group, there were no patients with subendocardial HE and all of them had some type of HE. According to these data, and excluding the patients with mid-myocardial HE in the successful ablation segment, the presence of epicardial HE in the ce-CMR images had a sensitivity of 84.6% and a specificity of 100.0% to predict an epicardial VA origin. The PPV obtained in this case was 100% and the NPV was 96.6%. Table 3 summarizes this information.

**Unsuccessful and still-inducible ventricular arrhythmia after radiofrequency ablation**

In 3 (3.8%) patients, the ablation procedure was unsuccessful. One of them was referred for VT ablation and the other two patients were

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**Table 3** Successful ablation site (endocardial vs. epicardial) depending on: (i) the presence of segments with epicardial hyper-enhancement (HE), (ii) the predominance of segments with epicardial HE, and (iii) the type of HE in the actual or ECG-suggested segment of origin

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<tr>
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<th>Endocardial successful ablation</th>
<th>Epicardial successful ablation</th>
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<tr>
<td>Segments with HE on ce-CMR, n (%)</td>
<td></td>
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<tr>
<td>No epicardial segments with HE</td>
<td>55 (94.8%)</td>
<td>3 (5.2%)</td>
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<tr>
<td>One or more segments with Epicardial HE</td>
<td>7 (36.8%)</td>
<td>12 (63.2%)</td>
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<tr>
<td>Segments with HE on ce-CMR, n (%)</td>
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<tr>
<td>Minority of segments with epicardial HE</td>
<td>61 (92.4%)</td>
<td>5 (6.2%)</td>
</tr>
<tr>
<td>Majority of segments with epicardial HE</td>
<td>1 (9.1%)</td>
<td>10 (90.8%)</td>
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<tr>
<td>HE on segment suggested by ECG (N = 37), n (%)</td>
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<tr>
<td>Absence</td>
<td>2 (100.0%)</td>
<td>0</td>
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<tr>
<td>Endocardial</td>
<td>6 (100.0%)</td>
<td>0</td>
</tr>
<tr>
<td>Transmural</td>
<td>26 (92.9%)</td>
<td>2 (7.1%)</td>
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<tr>
<td>Mid-myocardial</td>
<td>0</td>
<td>1 (100.0%)</td>
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<tr>
<td>Epicardial</td>
<td>0</td>
<td>0</td>
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<tr>
<td>HE on segment with successful RF ablation, n (%)</td>
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</tr>
<tr>
<td>Absence</td>
<td>3 (100.0%)</td>
<td>0</td>
</tr>
<tr>
<td>Endocardial</td>
<td>19 (100.0%)</td>
<td>0</td>
</tr>
<tr>
<td>Transmural</td>
<td>34 (94.4%)</td>
<td>2 (5.6%)</td>
</tr>
<tr>
<td>Mid-myocardial</td>
<td>6 (25.0%)</td>
<td>2 (25.0%)</td>
</tr>
<tr>
<td>Epicardial</td>
<td>0</td>
<td>11 (100.0%)</td>
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referred for scar-related PVC ablation. The patient referred for VT ablation presented subendocardial HE in the suspected SOO. One of the patients referred for scar-related PVC ablation had transmural HE in the suspected SOO, and both the endocardial and epicardial ablation were attempted. The other patient presented mid-myocardial HE in the suspected septal SOO. Thirteen (16.3%) patients remained inducible for other non-clinical VA. One of them (7.7%) had non-clinical PVCs, 6 (46.2%) had non-tolerated sustained monomorphic VT, and 6 (46.2%) had a non-tolerated polymorphic VT.

The number of patients with still-inducible VA after ablation was not significantly different for patients with transmural or mid-myocardial HE vs. those with other HE pattern distribution in the SOO [12 of 46 (26.0%) vs. 4 of 34 (11.8%), respectively; \( P = 0.113 \)]. The number of segments with HE was similar in the non-inducible and still-inducible patients after ablation (5.35 ± 3.24 vs. 6.00 ± 2.25 segments, \( P = 0.452 \)).

**Mid-myocardial hyper-enhancement**

Mid-myocardial HE in the SOO was identified in 8 (10.0%) patients, and 4 (50.0%) of them with non-ischaemic cardiomyopathy. Of the four patients with ischaemic cardiomyopathy, one patient also had hypertensive cardiomyopathy and the SOO was located in the septum, away from the inferior infarction scar. The distribution of the SOO with mid-myocardial HE was septal in 6 (75.0%) and in the free wall in 2 (25.0%) patients.

When the VA SOO was located in the septum, the successful ablation was performed from the LV in 4 (66.7%) patients. In both patients with a free wall SOO, the successful ablation was performed from the epicardium. A combined RV/LV or endocardial/epicardial mapping was performed in 7 (87.5%) patients, and RF applications from both the RV and LV were performed in 2 of them (25.0%). Radiofrequency was applied from the endocardium and the epicardium in 2 (25.0%) patients. Other VA (non-tolerated polymorphic VT) was induced in 3 (33.3%) patients after the elimination of the clinical one on the basal septum.

Of note, in all cases, the successful ablation site was that with the shortest distance to the centre of the HE region (mean distance: 5.95 ± 1.32 mm vs. 8.39 ± 2.63 mm; \( P = 0.015 \)). The thickness of the healthy tissue between the endocardial/epicardial surface and the scarred tissue boundary was also shorter in the successful ablation site (mean thickness: 4.03 ± 0.97 mm vs. 5.97 ± 1.87 mm; \( P = 0.003 \)), as detailed in Table 4 and Figure 4.

**Discussion**

**Main findings**

The present study indicates that the blinded analysis of the presence and distribution of the scar, obtained with pre-procedural conventional ce-CMR, may provide useful clinical information to localize the target ablation substrate of non-idiopathic VA and therefore to focus mapping in the ventricular area of interest, as these mostly (96.3%) originate in an LV segment with HE. In addition, this information can be used to plan the ablation procedure by helping to decide the approach: endocardial vs. epicardial in case of free wall VA or RV vs. LV septal mapping and ablation in case of septal VA.
Appropriately planning the approach for VT ablation is important for logistics and safety. Epicardial access after LV endocardial mapping, for which the patient should be anticoagulated, is not recommended and should be avoided. Therefore, the need to go to the epicardium after an endocardial mapping/ablation attempt would result in postponing the procedure to a second ablation attempt or to assume unnecessary risks for the patient. Alternatively, pericardium access could be gained before anticoagulation is needed for LV endocardial mapping/ablation in certain substrates, such as non-ischaemic cardiomyopathy. However, the incidence of epicardial VTs in non-ischaemic patients (42.9% in the present study) would result in nearly 60% unnecessary epicardial accesses. Therefore, in this subset of patients, a previous ce-CMR study may be recommended to plan the VT ablation approach. On the contrary, the low incidence of clinical VTs requiring epicardial ablation in ischaemic patients makes the recommendation of pre-procedural ce-CMR to identify patients with a scar extending into the epicardium controversial. Finally, epicardial ablation is a less-used technique; knowing the approach needed before beginning the procedure could help in deciding if the patient should be referred to a centre with experience in more complex ablations.

The presence of HE in non-ischaemic patients is variable. In primary prevention studies in patients with ICD, the incidence of HE was between 41 and 58%, and higher (71%) when secondary prevention patients were included. In line with the data in the present study showing 96.4% of non-ischaemic patients having HE, the vast majority of events in these studies were concentrated in the group of patients with HE.

Several small studies have shown that the location of HE in ce-CMR images is related to the VA substrate identified with the electroanatomical voltage map. In addition, a small study in non-ischaemic patients, only 48% of whom had delayed-enhancement indicative of scar, reported that the epicardial scar distribution in two patients required an epicardial ablation. However, the results of this study cannot be extrapolated to the general population of patients with scar-related VTs due to its small sample size, and the fact that the
majority (69%) of patients analysed had only PVCs as the index arrhythmia, explaining the low percentage of patients having delayed-enhancement and the low percentage needing epicardial ablation.\(^\text{2,22}\) In the present study, only 17.5% of patients had frequent PVCs associated with SHD. This explains why all patients had HE in some segments, and only 3 (3.8%) patients had the index arrhythmia (PVC in all cases) ablated in a segment without HE. Epicardial ablation was also more frequently needed in our study, probably due to difference in the patient profile.

**Diagnostic yield of pre-procedural contrast-enhanced cardiac magnetic resonance**

The presence of epicardial HE in any segment identified the epicardial origin of the VA with a high sensitivity (80%) and specificity (88.7%). However, when considering a predominant epicardial scar pattern instead of the simple presence of epicardial HE in any segment, the specificity increased to 98.4%, at the cost of a decrease in sensitivity to 66.7%. Although these values are comparable with those obtained with the ECG analysis of the VTs, the major advantage of using ce-CMR is the lack of dependence on 12-lead surface ECG availability and its analytical limitations, especially in fast VTs.\(^\text{6,8}\)

Sometimes patients have large, complex scar regions with varying distribution patterns through the LV wall, or these scars are present in different segments in the same ventricle. In these cases, the information provided by ECG could be useful to determine the segment in which the VA is originating. The classical algorithms for the identification of VA SOO by ECG analysis were obtained from patients with ischaemic heart disease. In the present study, the Miller algorithm was used to identify the segment of VA origin only in ischaemic patients, obtaining a 75.5% match with the actual ablation segment. One reason for this low accuracy was that the algorithm is only useful for patients with inferior or anterior infarctions. In our series, 3 of 49 (6.1%) patients had septal infarctions and so the algorithm could not be applied. Another reason for this low accuracy is that, according to the adaptation of the 12-segment electrophysiology model to the 17-segment model described here, the algorithm only defines the origin in Segments 3, 4, 5, 13, and 14 of the 17-segment model. ECG morphology is not defined for medial segments and basal anterolateral segments. If ECG algorithms to regionalize the SOO and applicable to non-ischaemic patients are developed in the future, the combination of the ECG with the ce-CMR images could determine an endocardial vs. epicardial origin with even higher sensitivity and specificity. Assuming a hypothetical perfect match between ECG-suggested SOO and the actual successful ablation segment, a sensitivity of 84.6% and a specificity of 100% could be obtained.

**Patients with mid-myocardial hyper-enhancement**

Mid-myocardial HE in the SOO is not frequent (10% in the present series) and probably depends on the underlying substrate, the preferential location being the interventricular septum. Contrary to previous reports,\(^\text{23}\) eight of the nine clinical VT ablation attempts in these cases were successful in the present series. This is probably related to mapping from both sides (endocardium/epicardium or RV/LV septum) in all but one of these patients and delivery of RF from both sides in four of the patients. Interestingly, the ablation was always successful at the site, in which the distance from the surface to the border/centre of the HE region was shorter. This suggests the usefulness of this measurement to deciding the right place for RF delivery.

On the other hand, a slightly higher percentage of patients remained inducible after ablation when the scar distribution was mid-myocardial in the basal septum. In a previous study, a similar percentage of still-inducible non-clinical VA was observed in patients with septal scars.\(^\text{23}\) In these cases, the limitations of ablation could be related not only to septal thickness, but also to the proximity of the conduction system and the risk of damaging it, precluding RF application.

Although, in this study, the number of patients with still-inducible VA after ablation was not significantly different for patients with transmural or mid-myocardial HE vs. those with other HE pattern distribution in the SOO, a clear divergence between the two groups is observed (26 vs. 12%, respectively; \(P = 0.113\)). The lack of statistical significance may be explained by an underpowered comparison due to the limited patient population. Further studies with more enrolled patients should be necessary to clarify this issue.

**Clinical implications**

Obtaining a pre-procedural conventional ce-CMR is of value for planning the VT ablation approach. In non-ischaemic patients, even the high incidence of epicardial VTs probably does not justify epicardial access before endocardial mapping for all the patients, especially with the possibility of using ce-CMR to guide the procedure. In ischaemic patients, the usefulness could be more limited if clinical VT elimination is the objective, because only a small proportion will require an epicardial ablation. However, if the objective is to render the patient non-inducible, ce-CMR could be of value to identify where the scar reaches the epicardium.

Figure 5 shows a proposed algorithm to identify the need for an epicardial, endocardial, RV, or LV access using only the ce-CMR information or both the ce-CMR information and the 12-lead ECG of the clinical VA. In the last case, information on the HE in the actual SOO of the clinical VA (ablation site) was used to create the decision algorithm. In the absence of any available algorithm to identify the SOO of an VA in non-ischaemic patients using the ECG information, we assumed that most electrophysiologists are able to identify the VA SOO by analysing the ECG morphology. A multicentre randomized study would be necessary to validate this algorithm. The main limitation for the application of this algorithm is that ce-CMR studies cannot be adequately executed or are contraindicated in most of the patients with implantable devices. During the study period, a ce-CMR could not be obtained in 34.8% of patients with SHD submitted for VT ablation. Systematically obtaining a ce-CMR before ICD implantation could be a good strategy, so that this information is available if an VT ablation is needed in the future.

Contrast-enhanced cardiac magnetic resonance could also be especially useful to identify mid-myocardial scars, because it allows measurement of the thickness of the healthy myocardium interposed between the scar and the endocardium/epicardium or RV/LV surface.
Proposed algorithm to identify an endocardial or epicardial site of origin (SOO) of a clinical ventricular arrhythmia (VA) in patients with structural heart disease (SHD) having a previous cardiac magnetic resonance (CMR) study. The algorithm has been created using the information from successful ablations of clinical ventricular tachycardia (VT). Numbers in the bottom line indicate 'successfully ablated patients with this approach/total number of patients meeting the algorithm conditions in each group'. *In some patients with transmural hyper-enhancement (HE), an epicardial approach may be needed. ‡The HE information from the actual SOO of the clinical VA (i.e. the segment where it was ablated) was used to create the decision algorithm. No algorithm able to identify the VA SOO in non-ischaemic patients using ECG information has been described in the literature. However, we assumed that most electrophysiologists are able to identify the VA SOO by analysing the ECG morphology.

**Figure 5** Proposed algorithm to identify an endocardial or epicardial site of origin (SOO) of a clinical ventricular arrhythmia (VA) in patients with structural heart disease (SHD) having a previous cardiac magnetic resonance (CMR) study. The algorithm has been created using the information from successful ablations of clinical ventricular tachycardia (VT). Numbers in the bottom line indicate ‘successfully ablated patients with this approach/total number of patients meeting the algorithm conditions in each group’. *In some patients with transmural hyper-enhancement (HE), an epicardial approach may be needed. ‡The HE information from the actual SOO of the clinical VA (i.e. the segment where it was ablated) was used to create the decision algorithm. No algorithm able to identify the VA SOO in non-ischaemic patients using ECG information has been described in the literature. However, we assumed that most electrophysiologists are able to identify the VA SOO by analysing the ECG morphology.
Limitations
The use of the ECG to identify the SOO and to increase the accuracy in predicting the successful ablation site is limited by the fact that the algorithms available are obtained from ischaemic patients. Although there are no algorithms developed to be used in non-ischaemic patients, it is assumed that the majority of electrophysiologists are able to regionalize the area of interest when the ECG during VT is available. However, even without the ECG information, the sensitivity and specificity of ce-CMR is high enough to be considered for VT ablation planning.

Another limitation of the study is its observational nature. The benefits of a pre-procedural ce-CMR in terms of ablation success, recurrences, and complications remain unanswered. The possible benefits should be assessed in a randomized trial.

Conclusion
The use of ce-CMR helps to identify an endocardial vs. epicardial VA origin and to plan the approach needed, especially in non-ischaemic patients. It also helps in deciding the RV vs. LV approach for septal scar-related VA with mid-myocardial HE. The additional benefit could be obtained by taking into account information from the 12-lead ECG to regionalize the SOO.

Supplementary material
Supplementary material is available at European Heart Journal online.

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