The goal of catheter ablation strategies for the treatment of scar-related ventricular tachycardia (VT) is the interruption of critical areas of slow conduction within the VT circuits responsible for the development and maintenance of VTs. Clinical studies have consistently shown the superiority of radiofrequency catheter ablation compared with standard medical therapy in controlling recurrent VT. However, even after an acutely successful ablation, the long-term freedom from recurrent VT remains suboptimal, especially in patients with nonischemic substrates where the recurrence rates for long-term follow-up can be as high as 77%. Identification of the optimal end points for VT ablation is crucial to improve the success rate of this procedure. The response to programmed electrical stimulation (PES) at the end of the procedure has been traditionally used to evaluate the acute success and predict long-term outcomes. Noninducibility by PES represents a classical end point for VT ablation and the only 1 endorsed by the current practice guidelines. Of note, a direct association between VT noninducibility at the end of the procedure and long-term arrhythmia-free survival has been suggested but not uniformly demonstrated. More recently, the increasing adoption of substrate-based ablation techniques, which target specific electrograms indexing slow conduction (ie, abnormal, split, and late electrograms) in sinus rhythm and reasonable surrogates for the VT isthmus, has been paralleled by an increasing need for new ablation end points. Although noninducibility at PES has been used as an end point also in studies evaluating substrate-based ablation approaches, other procedural end points have been described to validate the completeness of linear lesions and the elimination of abnormal potentials within the scar. This review will summarize the state of the art regarding procedural end points for catheter ablation of scar-related VT.

Invasive PES

Noninducibility at PES represents the most widely accepted end point for catheter ablation of scar-related VT. The most recent expert consensus document on VT ablation endorses noninducibility of the presumed clinical VT as the minimum end point for catheter ablation of scar-related VT; other end points beyond noninducibility are discussed but not specifically endorsed, because they have not been systematically validated. The bulk of the evidence supporting noninducibility at PES as a procedural end point derives from studies including patients with infarct-related VT (Table 2). Early experiences with catheter ablation in this clinical setting reported a significant association between noninducibility at the end of the procedure and VT-free survival. Subsequent studies including larger patient populations have provided mixed results. It is important to emphasize that none of these studies was specifically designed to perform a formal longitudinal evaluation of noninducibility as a predictor of postablation recurrences, and only 2 studies had a prospective randomized design. To better appraise the value of noninducibility as a predictor of ablation outcomes, we performed an exploratory pooled analysis of the available evidence using established methods (see the Data Supplement). Overall, a total of 1300 patients (age, 65±3 years; 89% men) with postinfarct VT and severe left ventricular (LV) dysfunction (average ejection fraction, 30.6±3.6%) were included in the analysis. Definition of noninducibility was heterogeneous among studies and included noninducibility of any VTs in 10 studies and noninducibility of only clinical or mappable VTs in 8 studies. Overall, 830 (64%) patients had no inducible VT at the end of the ablation procedure. After a median follow-up of 20 months (13–26 months), freedom from recurrent VT was achieved in 823 (63%) patients. On pooled analysis, no significant association was found between the rates of VT noninducibility and recurrence at follow-up (P=0.82). The same results were found when restricting the analysis only to studies with noninducibility of any VT as an end point (P=0.62; Figure 1). These results support the notion that noninducibility at PES is not a sufficient end point for catheter ablation of postinfarct VT because it is not uniformly associated with long-term VT-free survival. It is important to emphasize that several potential unmeasured confounders might interact with the results of our meta-analysis, including different periprocedural antiarrhythmic drug regimens (and adoption of preprocedural antiarrhythmic drug washout), different types of anesthesia, and heterogeneous PES protocols. As such, the results of our analysis should be viewed as hypothesis-generating only. VT induction with PES is a probabilistic rather than deterministic phenomenon, and multiple longitudinal evaluations with PES might increase the chances of VT induction indexing long-term outcome. The specific site of stimulation might

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Table 1. End Points for Ablation of Scar-Related VT

<table>
<thead>
<tr>
<th>Programmed Stimulation</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noninducibility of any VT at PES*</td>
<td>Established predictive value when performed from multiple sites (RV and LV) ≤3 extrastimuli</td>
<td>Not useful for patients without inducible VT; suboptimal negative predictive value; unclear significance of inducible nonclinical VTs</td>
</tr>
<tr>
<td>Noninducibility of any VT at NIPS (3–5 d postprocedure)</td>
<td>Improves predictive value when immediate postprocedural PES is negative or not feasible</td>
<td>Impact of early ablation in patients with positive NIPS is still unknown</td>
</tr>
<tr>
<td>Linear ablation lesions</td>
<td>Allows for rapid assessment of continuity of ablation lesions</td>
<td>Optimal pacing output unknown; no prospective validation; block across the line not demonstrated</td>
</tr>
<tr>
<td>Failure to capture with high-output pacing along the ablation line†</td>
<td>Allows for rapid assessment of block across the ablation line</td>
<td>Distinction between block and severe conduction delay across the line is not possible; no prospective validation</td>
</tr>
<tr>
<td>Change in GRS morphology with pacing from each sides of the line</td>
<td>Allows for rapid assessment of block across the ablation line</td>
<td></td>
</tr>
<tr>
<td>Conduction block across the line with pacing from each side of the line (activation mapping)</td>
<td>Allows for definite demonstration of block across the ablation line</td>
<td>Need for multiple catheters; no prospective validation</td>
</tr>
<tr>
<td>Ablation of abnormal EGMs (late potentials)</td>
<td>Empirical ablation of all the putative VT circuits within the scar; prospectively validated in observational studies</td>
<td>Complete elimination often difficult to achieve; late potentials not always present; need for extensive ablation</td>
</tr>
<tr>
<td>Elimination of late potentials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Failure to capture with high-output pacing†</td>
<td>Allows for assessment of lesion completeness (especially when elimination is not achieved)</td>
<td>May be time-consuming; no prospective validation</td>
</tr>
<tr>
<td>Change in late-potential activation (ie, late-potential dissociation, entrance block, further delay)</td>
<td>Indicates changes in the conduction properties of putative VT circuits within the scar</td>
<td>Late potentials not always present; need for extensive ablation</td>
</tr>
<tr>
<td>Scar dechanneling</td>
<td>Empirical ablation of all the putative VT circuits within the scar with the potential of limiting the amount of ablation necessary; prospectively validated</td>
<td>Dependent on accurate definition/visualization of channels defined with different voltage cutoffs and activation sequence of late potentials</td>
</tr>
<tr>
<td>Isolation of the scar core with box lesions</td>
<td>Allows for elimination of all the potential VT circuits, potentially reducing the amount of ablation necessary</td>
<td>Prospective validation ongoing</td>
</tr>
</tbody>
</table>

EGMs indicates electrograms; LV, left ventricle; NIPS, noninvasive programmed stimulation; PES, programmed electrical stimulation; RV, right ventricle; and VT, ventricular tachycardia.

*Except nonclinical fast (eg, cycle length <270 ms) VTs.
†Assessment of adequacy of point lesions (as part of a linear ablation strategy or to target local abnormal EGMs) can be validated with high-output pacing showing failure to capture (see text for details).

also play a role; in this respect, LV stimulation has been demonstrated to be superior to right ventricular (RV) stimulation for inducing clinical VT in patients with ischemic cardiomyopathy.31–33 Of note, the only study included in the pooled analysis that adopted LV stimulation was that by Carbucicchio et al; this study also reported 1 of the strongest associations between noninducibility at PES and long-term freedom from recurrent VT.

Recently, Santangeli et al35 prospectively compared RV stimulation with LV stimulation within the scar (as defined by conventional voltage criteria) in a series of 156 patients undergoing catheter ablation of postinfarction VT. The end point of this study was induction of clinical VT. PES (drive trains of 600/500/400 ms with ≤3 extrastimuli) was performed sequentially from the RV apex, outflow tract, and within the infarct scar defined by electroanatomic mapping. RV stimulation induced clinical VTs in 31% of cases, whereas stimulation within the scar induced clinical VTs in 69% of cases (risk ratio, 2.20; 95% confidence interval, 1.68–2.89; P=0.001). Notably, 13 (8%) patients had inducible VT only from the scar.35 It is important to emphasize that the relative merits of RV-only versus LV stimulation were not separately assessed for left bundle branch block versus right bundle branch VTs. In our experience, scar-related left bundle branch block VTs are more easily induced from the RV, whereas some right bundle branch block VTs are best induced with lateral LV stimulation; this is in line with the observation of right bundle branch block VT proarrhythmia from LV or biventricular pacing.34 It is conceivable that noninducibility of any VT achieved with a consistent stimulation protocol that includes triple extrastimuli from multiple RV and LV sites might provide incremental value in predicting long-term VT-free survival, although adequately designed prospective studies are needed to test this hypothesis. Based on the experience of catheter ablation of postinfarct VT, noninducibility at PES has been used as an ablation end point across all the spectrum of scar-related VTs.12 In patients with nonischemic substrates, few studies have evaluated the role of noninducibility as a predictor of survival free from recurrent VT after catheter ablation.35–37 Piers et al35 recently determined the value of noninducibility at PES in 45 consecutive patients with nonischemic cardiomyopathy and scar-related VT. In this study, inducibility of any VT at the end of the procedure was the strongest predictor of VT recurrence (hazard ratio, 8.20; 95% confidence interval, 2.37–28.43; P=0.001). Overall, these findings would support the appropriateness of noninducibility as an end point for catheter ablation of VT in nonischemic cardiomyopathy as well, although further studies are warranted to validate these results.

Limitations of Invasive PES as an End Point for Catheter Ablation of Scar-Related VT

As mentioned, thus far no study has been specifically designed to test the value of noninducibility at PES in predicting VT
recurrences after catheter ablation, and none of the published studies had a prospective randomized design. Multiple VT morphologies can typically be induced with PES, and it is particularly challenging to evaluate the clinical relevance of previously undocumented VTs. The approach currently adopted by most institutions is to target every inducible VT except fast nonclinical VTs. In patients with coronary artery disease, there is some evidence that using a cycle length cutoff of 270 ms would distinguish between nonclinical VTs with no prognostic relevance and nonclinical VTs that should be targeted for ablation. Slow VTs also tend to recur more often as compared with fast VTs; recently, we found an association between persistent inducible VT with a cycle length >300 ms and VT recurrence during follow-up. However, no cycle length cutoff value has been validated in adequately designed prospective studies including a large number of patients with different substrates. Lack of VT inducibility before ablation represents another limitation of PES because it can occur in a substantial proportion of patients referred for catheter ablation of scar-related VT. In this regard, multiple site stimulation (including LV stimulation) might increase the chances of inducing VT. Whether repeating PES during intravenous isoproterenol infusion provides any additional benefit is also a matter of controversy and warrants further investigation. Finally, the optimal time point to perform PES is yet unknown.

Table 2. Summary of Clinical Studies Using Noninducibility at PES as the End Point for Catheter Ablation of Postinfarct VT

<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>No. of Patients</th>
<th>EF, %</th>
<th>End Point</th>
<th>PES Protocol</th>
<th>Acute End Point</th>
<th>Follow-Up, mo</th>
<th>VT Recurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morady et al12</td>
<td>1993</td>
<td>15</td>
<td>27</td>
<td>Noninducibility of clinical VT</td>
<td>600/400/350 ms, S4, 2 RV sites</td>
<td>80%</td>
<td>9</td>
<td>13%</td>
</tr>
<tr>
<td>Kim et al21</td>
<td>1994</td>
<td>21</td>
<td>32</td>
<td>Noninducibility of any VT</td>
<td>No information</td>
<td>29%</td>
<td>13</td>
<td>45%</td>
</tr>
<tr>
<td>Rothman et al13</td>
<td>1997</td>
<td>35</td>
<td>24</td>
<td>Noninducibility of any VT</td>
<td>600/400 ms, S4, 2 RV sites; protocol repeated after 30 min waiting period</td>
<td>31%</td>
<td>14</td>
<td>31%</td>
</tr>
<tr>
<td>Stevenson et al15</td>
<td>1998</td>
<td>52</td>
<td>33</td>
<td>Noninducibility of any VT</td>
<td>600/400 ms, S4, 2 RV sites (only 1 site in 5 cases)</td>
<td>40%</td>
<td>18</td>
<td>31%</td>
</tr>
<tr>
<td>Ortiz et al23</td>
<td>1999</td>
<td>34</td>
<td>31</td>
<td>Noninducibility of any VT</td>
<td>600/400 ms, S4, 2 RV sites</td>
<td>67%</td>
<td>26</td>
<td>38%</td>
</tr>
<tr>
<td>El-Shalakany et al20</td>
<td>1999</td>
<td>15</td>
<td>26</td>
<td>Noninducibility of any VT</td>
<td>3 drive trains (NS), S4</td>
<td>93%</td>
<td>15</td>
<td>27%</td>
</tr>
<tr>
<td>Calkins et al9</td>
<td>2000</td>
<td>119</td>
<td>31</td>
<td>Noninducibility of any mappable VT</td>
<td>NS drive trains, S4, 2 RV sites</td>
<td>89%</td>
<td>8</td>
<td>46%</td>
</tr>
<tr>
<td>Borger et al12</td>
<td>2002</td>
<td>89</td>
<td>29</td>
<td>Noninducibility of any mappable VT</td>
<td>600/500/400 ms, S4, 2 RV sites</td>
<td>78%</td>
<td>34</td>
<td>23%</td>
</tr>
<tr>
<td>Della Bella et al16</td>
<td>2002</td>
<td>124</td>
<td>34</td>
<td>Noninducibility of clinical VT</td>
<td>600/500/400 ms, S4, 2 RV sites</td>
<td>73%</td>
<td>41</td>
<td>28%</td>
</tr>
<tr>
<td>O’Donnell et al22</td>
<td>2002</td>
<td>112</td>
<td>NR</td>
<td>Noninducibility of any VT</td>
<td>600/400 ms, S6, 1 RV site (apex)</td>
<td>38%</td>
<td>61</td>
<td>23%</td>
</tr>
<tr>
<td>Segal et al24</td>
<td>2005</td>
<td>40</td>
<td>36</td>
<td>Noninducibility of any VT</td>
<td>600/400 ms, S4, 2 RV sites</td>
<td>60%</td>
<td>36</td>
<td>57%</td>
</tr>
<tr>
<td>Volkmer et al27</td>
<td>2006</td>
<td>47</td>
<td>30</td>
<td>Noninducibility of any VT</td>
<td>NS drive trains, S4, 2 RV sites</td>
<td>81%</td>
<td>25</td>
<td>25%</td>
</tr>
<tr>
<td>Stevenson et al29</td>
<td>2008</td>
<td>231</td>
<td>25</td>
<td>Noninducibility of any VT with a CL &lt;20 ms of the clinical VT; faster VTs targeted at the discretion of the operator</td>
<td>600/400 ms, S4, 2 RV sites</td>
<td>49%</td>
<td>6</td>
<td>47%</td>
</tr>
<tr>
<td>Carbucicchio et al7</td>
<td>2008</td>
<td>95</td>
<td>36</td>
<td>Noninducibility of any VT</td>
<td>600/500/400 ms, S4, multiple RV/LV sites</td>
<td>65%</td>
<td>22</td>
<td>34%</td>
</tr>
<tr>
<td>Tanner et al30</td>
<td>2010</td>
<td>63</td>
<td>30</td>
<td>Noninducibility of any clinical VT and VTs slower than clinical VT</td>
<td>600/400 ms, S4, 2 RV sites</td>
<td>81%</td>
<td>12</td>
<td>49%</td>
</tr>
<tr>
<td>Kuck et al2</td>
<td>2010</td>
<td>52</td>
<td>34</td>
<td>No information</td>
<td>No information</td>
<td>52%</td>
<td>23</td>
<td>53%</td>
</tr>
<tr>
<td>Tung et al10</td>
<td>2010</td>
<td>54</td>
<td>31</td>
<td>Noninducibility of any VT</td>
<td>600/400 ms, S4, 2 RV sites</td>
<td>76%</td>
<td>24</td>
<td>15%</td>
</tr>
<tr>
<td>Dinov et al19</td>
<td>2012</td>
<td>102</td>
<td>32</td>
<td>Noninducibility of any VT</td>
<td>500/430/370/330 ms, S2, 1 RV site (apex)</td>
<td>76%</td>
<td>14</td>
<td>42%</td>
</tr>
</tbody>
</table>

CL indicates cycle length; EF, ejection fraction; LV, left ventricle; NS, not specified; PES, programmed electrical stimulation; RV, right ventricle; S4, 3 extrastimuli; S6, 5 extrastimuli; and VT, ventricular tachycardia.
Noninvasive PES

In our institution, NIPS a few days after the catheter ablation procedure has been used to identify patients at increased risk of VT recurrence. In a prospective study, out of 189 consecutive patients with VT and structural heart disease who had no inducible clinical VT at the end of the ablation procedure, 132 (70%) underwent NIPS from the RV implantable cardioverter-defibrillator lead (drive trains of 600/400 ms; ≤3 extrastimuli; a mean of 3.1±2.1 days after ablation). NIPS confirmed VT noninducibility in 45% of cases. Nonclinical VT only was inducible in 37% of patients and clinical VT in 18%. Patients who had their clinical VT induced at NIPS a few days after the procedure were more likely to be treated with high-dose amiodarone before the procedure and to have their amiodarone dose either decreased or discontinued after ablation. Such a change in the antiarrhythmic drug status together with differences in autonomic tone and degree of sedation with anesthesia, as well as electrophysiological recovery of ablated tissue, might have contributed to the additional yield of NIPS above and beyond PES immediately after the procedure. At 1-year follow-up, patients without any inducible VT at NIPS had significantly better arrhythmia-free survival compared with patients with inducible clinical VT or inducible nonclinical VT only (85% versus 30% versus 65%; P<0.001 and 0.01, respectively; Figure 2). These findings would suggest that performing NIPS a few days after the procedure as an end point for catheter ablation of scar-related VTs should be strongly considered. The benefit of early intervention with repeat ablation in NIPS-positive patients requires further investigation in adequately designed studies.

End Points for Substrate-Based Ablation

Substrate-based ablation approaches have been developed to address the fact that most VTs in the setting of structural heart disease are either not inducible or poorly tolerated, precluding detailed activation and entrainment mapping. Substrate ablation is based on the transection of putative VTs exit sites and isthmuses within the dense scar with linear or clustered ablation lesions and the elimination of abnormal electrograms that identify areas of slow conduction (ie, split electrograms and late potentials). The increasing adoption of substrate-based ablation approaches has been paralleled by an increasing need for novel end points beyond noninducibility to evaluate the completeness of linear lesions and the effective elimination of abnormal electrograms.

Figure 1. Weighted meta-regression analysis assessing the value of noninducibility at programmed electric stimulation (PES) immediately after the procedure in predicting long-term arrhythmia-free survival in patients undergoing catheter ablation of postinfarct ventricular tachycardia (VT). The rates (y axis) of VT recurrence at follow-up are plotted against the rate of VT noninducibility at the end of the procedure for each included study (x axis). Increasing rates of VT noninducibility are not linearly correlated to an increase in long-term procedural success. Note that weights are based on stratum sample size. Study included (1) Kim et al., (2) Rothman et al., (3) O’Donnell et al., (4) Stevenson et al., (5) Stevenson et al., (6) Kuck et al., (7) Segal et al., (8) Carbucicchio et al., (9) Ortiz et al., (10) Della Bella et al., (11) Tung et al., (12) Dinov et al., (13) Borger et al., (14) Morady et al., (15) Volkmer et al., (16) Tanner et al., (17) Calkins et al., and (18) El-Shalakany et al.

Figure 2. One-year arrhythmia-free survival based on response to noninvasive programmed stimulation (NIPS) performed 1 to 7 d after ventricular tachycardia ablation. Data from Frankel et al.,
Linear Ablation Lesions and Point Lesion Assessment

Substrate-based linear ablation has been developed with the intent of replicating the surgical experience with subendocardial resection. According to the original description by Marchlinski et al, this ablation strategy included contiguous lesions delivered from the dense infarct area (as defined by standard voltage criteria) through the infarct border zone and connecting to anatomic barriers or normal myocardium. Linear lesions are also commonly deployed to transect channels visualized after adjusting voltage cutoffs on color isopotential electroanatomic maps; these channels, particularly when associated with late potentials, have been correlated with VT isthmuses as defined by entrainment mapping. In this regard, it is important to emphasize that visualization of voltage channels and late potentials may be subject to error: identification of local activation at the site of catheter contact can be challenging and may require pacing from multiple sites (and different cycle lengths) to separate local activation from far-field signals. Recent evidence also suggests a critical degree of tissue–catheter contact to detect the presence of late potentials within scar, which could also influence the ability of isopotential electroanatomic maps to accurately identify putative VT channels. Finally, a linear ablation strategy is often required in mappable VTs to interrupt conduction through a broad isthmus, as defined by entrainment mapping. In these situations, even if acute VT termination is achieved, ablation should be extended to cover the entire width of the isthmus to prevent VT recurrence, analogous to what is done in...
cavotricuspid isthmus–dependent macroreentrant atrial flutter (Figure 3). Typically, linear lesions are deployed with sequential point-by-point ablation. The effectiveness of each point lesion is assessed by monitoring multiple parameters, including adequate tissue–catheter contact validated with fluoroscopy and intracardiac echocardiography (ICE), impedance monitoring, electric unexcitability with high-output pacing, and elimination of high-frequency signals representing near-field activation. Once a linear lesion has been deployed, it is important to define electrophysiological end points to assess for completeness (Table 1); thus far, there is no established method to confirm block across a linear lesion in the setting of VT ablation, although some criteria have been suggested but not validated in large studies.45 In theory, when an ablation line is complete, high-output pacing along the line should result in unexcitability, similar to what has been reported in the context of catheter ablation of atrial fibrillation.46 Based on previous clinical experiences, most investigators use a pacing output of 10 mA and a pulse width of 2 ms to confirm unexcitability,47 although capture within the dense scar can frequently still be achieved using higher pulse strengths.48 Therefore, the optimal pacing output to confirm electric unexcitability after ablation is still undefined. Electrophysiological criteria for confirmation of block across a line of ablation have not been established. Recently, we described a novel end point for confirmation of block across a linear ablation lesion, namely the change in QRS morphology with pacing at a site adjacent to the ablation lesions.43 The index case was a 44-year-old man with a history of Tetralogy of Fallot and scar-related VT, which was documented by entrainment maneuvers to be clockwise macrore-entry below the pulmonic valve (Figure 4). The exit site of the VT was under the pulmonic valve on the posterior aspect of the conal septum; the isthmus site was the conal free wall of the RV outflow tract. A single radiofrequency lesion delivered at the isthmus site terminated the VT; after ablation, pace mapping proximal to the isthmus/ablation site resulted in a dramatic change in QRS morphology, with a superior axis that no longer matched the clinical VT but matched the pace map obtained from the conal free wall before ablation. In this case, the change in pace maps pre- and postablation demonstrated that a line of block had been created with ablation, thereby resulting in a different exit out of the scar from the pacing site (Figure 4).43 This report highlights the value of pace mapping to confirm block across a linear ablation lesion; however, this technique does not definitively allow for distinction between complete block and extreme delay created by the ablation. The ultimate demonstration of block across a linear lesion can be achieved with detailed activation mapping when pacing from each side of the ablation line. The major drawback of activation mapping is that it requires at least 2 catheters and is time-consuming. Block is definitively demonstrated when the distal side of the line (close to the exit of the VT circuit) is activated later than the outer loop and the putative VT exit site at the border zone of the scar (Figure 5). Bidirectional block can be confirmed with pacing from the distal aspect of the line; the latter is crucial when bidirectional rotation across an isthmus has been clinically documented, such as in the case of clockwise or counterclockwise re-entrant VT using the mitral isthmus in the setting of an inferior myocardial infarction.49,50 Another technique to approximate block across a linear lesion is to analyze the activation delay to a site immediately distal (closer to the VT exit) to the ablation line when pacing proximal to the line (closer to the VT entrance). Although no absolute timing value can be used as a proof of conduction

### Table 3. Summary of Studies Evaluating Substrate-Based Ablation Targeting Late Potentials

<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>No. of Patients</th>
<th>Type of Substrate</th>
<th>LVEF, %</th>
<th>End Point Assessed</th>
<th>EPI Map/Abl</th>
<th>FU, mo</th>
<th>VT Recurrence</th>
<th>Complications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arenal et al59</td>
<td>2003</td>
<td>24</td>
<td>21 ICM, 2 NICM, 1 ToF</td>
<td>30±9</td>
<td>Elimination of late potentials</td>
<td>No</td>
<td>9±4</td>
<td>21%</td>
<td>None</td>
</tr>
<tr>
<td>Volkmer et al27</td>
<td>2006</td>
<td>25</td>
<td>ICM</td>
<td>30±8</td>
<td>Elimination of late potentials</td>
<td>No</td>
<td>26±14</td>
<td>29%</td>
<td>Not reported</td>
</tr>
<tr>
<td>Nogami et al53</td>
<td>2008</td>
<td>18</td>
<td>ARVC</td>
<td>NR</td>
<td>Change of late potentials*</td>
<td>No</td>
<td>61±38</td>
<td>33%</td>
<td>Not reported</td>
</tr>
<tr>
<td>Garcia et al52</td>
<td>2009</td>
<td>13</td>
<td>ARVC</td>
<td>NR</td>
<td>Elimination of late potentials</td>
<td>Yes</td>
<td>18±13</td>
<td>33%</td>
<td>None</td>
</tr>
<tr>
<td>Bai et al71</td>
<td>2011</td>
<td>26</td>
<td>ARVC</td>
<td>53±10</td>
<td>Elimination of late potentials</td>
<td>Yes</td>
<td>39±4</td>
<td>15%</td>
<td>1 groin hematoma</td>
</tr>
<tr>
<td>Berruezo et al56</td>
<td>2012</td>
<td>11</td>
<td>ARVC</td>
<td>55±7</td>
<td>Elimination of late potentials</td>
<td>Yes</td>
<td>11 (6–24)</td>
<td>9%</td>
<td>1 RV puncture during epicardial access</td>
</tr>
<tr>
<td>Di Biase et al54</td>
<td>2012</td>
<td>43</td>
<td>ICM</td>
<td>24±8</td>
<td>Elimination of late potentials±failure to capture</td>
<td>Yes</td>
<td>21 (19–25)</td>
<td>19%</td>
<td>1 groin hematoma</td>
</tr>
<tr>
<td>Jais et al52</td>
<td>2012</td>
<td>70</td>
<td>56 ICM, 14 NICM</td>
<td>35±10</td>
<td>Elimination of late potentials</td>
<td>Yes</td>
<td>22 (14–27)</td>
<td>32%</td>
<td>1 cardiac tamponade, 1 RV perforation</td>
</tr>
<tr>
<td>Vergara et al72</td>
<td>2012</td>
<td>50</td>
<td>36 ICM, 14 NICM</td>
<td>32±9 ICM; 36±10 NICM</td>
<td>Elimination of late potentials</td>
<td>Yes</td>
<td>13±4</td>
<td>20%</td>
<td>Not reported</td>
</tr>
<tr>
<td>Arenal et al57</td>
<td>2013</td>
<td>59</td>
<td>ICM</td>
<td>30±11</td>
<td>Elimination of late potentials</td>
<td>No</td>
<td>39±21</td>
<td>42%</td>
<td>No major</td>
</tr>
<tr>
<td>Tung et al73</td>
<td>2013</td>
<td>21</td>
<td>15 ICM, 2 NICM, 2 ARVC, 1 sarcoid, 1 noncompaction, 1 chagas</td>
<td>25 (25–30)</td>
<td>Change or elimination of late potentials±failure to capture±impedance drop &gt;10</td>
<td>Yes</td>
<td>11 (6–18)</td>
<td>14%</td>
<td>Not reported</td>
</tr>
</tbody>
</table>

*Abi indicates ablation; ARVC, arrhythmogenic right ventricular cardiomyopathy; EPI, epicardial; FU, follow-up; ICM, ischemic cardiomyopathy; LVEF, left ventricular ejection fraction; Map, mapping; NICM, nonischemic cardiomyopathy; and ToF, Tetralogy of Fallot.

*Change of late potentials includes elimination, dissociation, entrance block, or further delay. Follow-up duration is expressed as mean±SD or median (interquartile range).
block, a conduction time across the line equal or longer than the VT cycle length (when pacing at or closer to the VT cycle length) can be used as a reasonable surrogate for complete (unidirectional) block (Figure 5). It is important to emphasize that even adopting the maneuvers described above, in our experience, the achievement of block across a linear lesion is particularly challenging and seems to be even more difficult to demonstrate. Current ablation technologies do not typically deliver transmural lesions in the ventricle. Therefore, the achievement of block with linear ablation requires the presence of anatomic barriers (pre-existent scar or anatomic structures) that form the boundaries of the VT isthmus, together with anchors (pre-existent intramyocardial scar) localized in the subendocardium (or subepicardium). The development of reliable techniques to both create effective linear lesions and reliably assess their electrophysiological effect including the presence of bidirectional block should stand the test of follow-up as a better index of arrhythmia-free survival.

Ablation/Elimination of Late Potentials
Regions with delayed and fragmented conduction bordering on scar tissue have been demonstrated to be essential components of circuits underlying re-entrant ventricular arrhythmias. Fragmented electrograms can be recorded throughout the scar and are not specific for VT circuit components, whereas isolated and late potentials have been demonstrated to be relatively specific markers for VT circuits and are currently incorporated as a target in most substrate-based ablation strategies. Studies evaluating the role of late potential ablation in scar-related VT adopted heterogeneous procedural end points to ensure completeness of ablation, ranging from complete elimination of late potentials to failure to capture with high-output pacing (or a combination of the 2 criteria; Table 3). With currently available ablation tools, complete abolition of late potentials is not always achievable. In a prospective study, Vergara et al reported complete elimination of late potentials in 42 of 50 (84%) patients. Similarly, in a recent observational study, Jais et al targeted high-frequency late potentials (so-called local abnormal ventricular activities) in a series of patients with scar-related VT; the authors were able to successfully eliminate these abnormal electrograms in only 70% of cases. The same results have been reported by Nogami et al in 18 patients with arrhythmogenic RV cardiomyopathy. Late potentials were present in 16 of 18 patients and were successfully eliminated by radiofrequency ablation in only 5 of 16 (31%) cases. In an additional 5 patients, ablation resulted in a significant change (but not elimination) of late-potential activation, which included electric dissociation, second-degree entrance block, or further delay. In the remaining 6 patients, ablation had no effect on late potentials. In this study, any change of late potentials (elimination or change in activation) was found to be associated with lower VT recurrence rate during follow-up. In a recent prospective study, Di Biase et al adopted a combination of late potential elimination and lack of capture with high-output pacing (20 mA output; pulse duration, 10 ms) to confirm effective ablation. High-output pacing is particularly helpful in areas where late potentials are persistently recorded despite extensive ablation. In these situations, lack of (global) capture is best explained by either far-field recording or local capture with exit block and suggests that one can discontinue radiofrequency application. Of note, studies evaluating the activation patterns of late potentials have mostly suggested a sequential activation pattern from the border of the scar through well-defined channels. The identification of such channels of activation will likely increase in the near future, owing to a more extensive adoption of multipolar electrode mapping with smaller electrodes and tighter interelectrode distance. Once a specific sequence of late-potential activation has been identified, focal ablation of the earliest late potential may eliminate a consecutive series of late potentials that may be critical for supporting a re-entrant circuit. This concept has been highlighted by Berruezo et al in a series of patients with VT in the setting of arrhythmogenic RV cardiomyopathy. The authors performed high-density endocardial–epicardial substrate maps in 11 consecutive arrhythmogenic RV cardiomyopathy patients and were uniformly able to identify discrete areas with a gradient of activation of late potentials, referred to as conducting
channels. Notably, radiofrequency application at the putative entrance sites of the conducting channels, defined as the site displaying the earliest late potential, resulted in the elimination of a row of late potentials within the conducting channel. Such entrance sites were typically localized in the scar border zone. The end point of the ablation strategy described by Berrozo et al was elimination of all the conducting channels (ie, scar dechanneling) and resulted in noninducibility in 100% of patients and a VT-free survival of 91% during a median follow-up of 11 months.

One of the limitations of late-potential ablation is the likely bystander nature of many of the late potentials; targeting these electrograms will not confer any clinical benefit. Previous data suggest that this may be more common in inferior infarctions, where large areas of myocardium can be activated late in the normal process of activation in sinus rhythm. Further studies are warranted to better understand the clinical relevance and relation to clinical arrhythmias of late potentials recorded within the scar, to identify the specific electrograms that are relevant to the development of VT; the latter might be particularly challenging, because a given late potential may be a bystander for some VT circuits but may participate in others. The second major limitation is related to the site-dependent nature of pacing required to bring out late

Figure 7. Example of box lesion set with achievement of electric isolation of the core of the ventricular tachycardia (VT) circuit. A, A voltage map (right anterior oblique view) of a patient with a large anterior myocardial infarction; the core of the VT circuit has been boxed by contiguous ablation lesions delivered at the junction between the dense scar and the scar border zone. B, After completion of the box lesion set, a multipolar catheter (pentaray, P) has been positioned within the ablated area (right anterior oblique view). C, Pacing from the multipolar catheter demonstrates local capture (red arrows) with exit block, proving isolation of the arrhythmogenic core. Pacing within the boxed area was repeated from multiple different sites, always demonstrating exit block.
potentials. For instance, early studies have suggested that RV pacing might allow detection of late potentials in more patients compared with sinus rhythm. Identifying best pacing sites to identify late potentials based on scar location and VT morphology has not been established. The number of pacing sites that are required to optimally define clinically relevant late activation also remains to be determined. Third, the optimal recording technique to identify late potentials and their elimination with ablation related to electrode size requires further study. Finally, the need for additional remapping to establish total elimination of late potentials from different pacing sites still needs to be determined.

Box Lesion Set With Loss of Excitability in the Core of VT Substrate Abnormalities
The concept of a box lesion set to isolate the critical core of VT circuitry has been recently developed by our group and is being actively investigated in a multicenter clinical study. From a physiological perspective, the critical zones of slow conduction responsible for VT maintenance are typically located within the dense scar and are frequently associated with the presence of late potentials. In an effort to limit the number of lesions required to eliminate all the areas critical for VT maintenance within the dense scar (eg, putative VT channels and late potentials), we developed the box-type lesion set, with the procedural end point of electric unexcitability within the scar core. The box-type substrate ablation is a stepwise approach that starts with the identification of the area of interest within the dense scar that is related to the patient’s clinical and induced VTs based on conventional criteria, including voltage channels, sites with late potentials, sites with good pace maps and long stimulus-to-QRS intervals, isthmus sites defined by entrainment mapping, and sites of VT termination with ablation (when possible). Once identified, the area of interest is boxed by linear ablation lesions delivered within the dense scar (<0.5 mV) using anatomic anchors (when present) to minimize the amount of ablation necessary (Figure 6). At the end of the box lesion set, loss of (global) capture when pacing at high output from multiple regions within the ablation set should be confirmed. Theoretically, one should be able to demonstrate local capture with exit block when pacing within the boxed area. In this regard, direct recording with a multielectrode catheter, preferably with small electrodes and tight interelectrode space, can be particularly valuable (Figure 7). Caution should be exercised in the presence of persistent global capture from the boxed area, especially when the paced QRS morphology does not match the paced QRS obtained before ablation or that obtained with pacing along the scar border zone. Indeed, high-output pacing might result in a large virtual electrode that can overcome the electric barriers created by ablation or the pre-existing anatomic anchors used to box in the VT core, resulting in the capture of myocardial tissue at distance and unrelated to VT circuitry.

If the end point of electric isolation is not achieved after the initial lesion set, the ablation lesions should be carefully remapped for potential gaps and additional lesion placed to target late potentials within the box. As indicated it is not expected that the isolation is transmural in nature in most patients. We postulate that the isolation of the endocardial aspect of the region of interest can be achieved if an intramural dense scar forms an effective electric barrier preventing transmural conduction (Figure 6). This is consistent with the compartmentalization of the RV from the LV documented in patients with midmyocardial septal scar in the setting of nonischemic cardiomyopathy. This new substrate-based approach may minimize the amount of ablation necessary to eliminate all the potential VT circuits within the dense scar and is based on a strong physiological rationale. A multicenter study is actively investigating the clinical benefit of this approach.

Online Imaging for Direct Visualization of Lesion Formation
Although the selection of ablation targets should always rely on information derived from established electrophysiological maneuvers and analysis of electrograms, direct visualization of lesion formation might provide valuable information on the adequacy and completeness of the lesions. We routinely perform online imaging with ICE to monitor tissue–catheter contact, catheter stability, and lesion formation during ablation of scar-related VT (Figure 8). In a previous study, Ren et al correlated the ICE imaging of intramural swelling during radio-frequency delivery with lesion size at pathological analysis in a swine model of chronic myocardial infarction, thus providing the rationale for real-time ICE monitoring of lesion formation. The use of other imaging modalities such as cardiac MR is still at the investigational stages, although early experiences have shown promising results. In particular, T2-weighted cardiac MR imaging has been demonstrated to identify hyperintense myocardial areas correlating with lesion size on pathology and noncontrast T1-weighted sequences have been used to monitor lesion formation. Gadolinium contrast-enhanced sequences represent the gold standard for noninvasive visualization of ablation lesions; preliminary reports suggest that a good correlation with pathological analysis can be achieved.
by imaging intermediate late-enhancement patterns as early as 1 minute after contrast injection.68 On the contrary, owing to the relatively long half-life of elimination of gadolinium (1–2 hours), gadolinium contrast-enhanced cardiac MR seems less useful for the serial assessment of lesion formation.68

Conclusions

Catheter ablation of VT is a well-established treatment for scar-related VT, although the long-term outcomes still remain suboptimal. Traditionally, noninducibility with programmed ventricular stimulation has been used as the end point for catheter ablation of scar-related VT with inconsistent results. A pooled analysis of the available evidence does not support the adoption of noninducibility as the only end point for catheter ablation of scar-related VT and highlights the importance of evaluating novel end points to improve ablation outcomes. Observational data suggest that repeat programmed stimulation from the implantable cardioverter-defibrillator (NIPS) several days after the procedure may provide incremental predictive value for long-term VT-free survival.38 The increasing frequency catheter ablation for infarct-related ventricular tachycardias. A meta-analysis: comparison of results obtained with coronary artery disease.

References


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Disclosures

None.


27. Santangeli et al. End Points for Ventricular Tachycardia Ablation 959


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http://circep.ahajournals.org/content/7/5/949

Data Supplement (unedited) at:
http://circep.ahajournals.org/content/suppl/2014/10/16/CIRCEP.114.001585.DC1
Supplemental Material

Data Sources and Selection


Study Selection

Studies were included if they: enrolled patients undergoing catheter ablation of post-infarct VT; adopted noninducibility at PES as a procedural endpoint; reported the rates of VT recurrence over follow-up in patients who were noninducible at the end of the procedure and in those that failed to achieve the procedural endpoint.

Data Extraction and Analysis

Reviewers extracted the data regarding inclusion criteria, the total number of patients, the baseline left ventricular ejection fraction, the PES protocol, the definition of noninducibility, the number of patients who achieved the acute procedural endpoint, the rates of VT recurrence over follow-up, the duration of study follow-up. Categorical data are expressed as number and percentages, continuous data are expressed as mean and standard deviation. In order to appraise the impact of noninducibility at PES on long-term outcomes, a weighted linear correlation
analysis was carried out. Weights were assigned to the individual studies based on the study sample size. Correlation analyses were assessed with a weighted Pearson’s test, plotting the rate of noninducibility at PES against the long-term VT recurrence rate. Statistical level of significance was defined at a $P < 0.05$ [two tailed]. Analyses were performed using the STATA 12.1 software package (Stata Corporation, College Station, Texas, USA).