ECG Criteria to Identify Epicardial Ventricular Tachycardia in Non-Ischemic Cardiomyopathy

Running title: Criteria for epicardial ventricular tachycardia

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Abstract

Background: ECG criteria identifying epicardial (EPI) origin for ventricular tachycardia (VT) in non-ischemic cardiomyopathy (NICM) have not been determined. Endocardial (ENDO) and EPI basal left ventricle fibrosis characterizes the VT substrate.

Methods and Results: We assessed the QRS from 102 basal-superior/lateral EPI and 67 comparable ENDO pacemaps (PM) in 14 patients with NICM. Pacemapping focused on low bipolar voltage areas. Published morphology: q wave in lead I (QWL1), no q waves in inferior leads and interval criteria: pseudo-delta wave (PdW) ≥34ms, intrinsicoid deflection time ≥85ms, shortest RS complex ≥121ms and maximum deflection index (MDI) ≥0.55 were assessed for ability to identify EPI origin. Sixteen EPI and 8 ENDO of the 34 mapped VTs (71%) in the study population and 14 EPI and 7 ENDO VTs from an 11 patient validation cohort were localized to basal-superior/lateral left ventricle and corroborated pacing data. A QWL1 was seen in EPI but not ENDO PMs (91% vs 4%; p<0.001), identified 14/16 EPI VTs (sensitivity 88%) and was seen in 1/8 ENDO VT’s (specificity 88%). None of the remaining criteria achieved similar sensitivity without specificity <50%. We identified 4 criteria (q waves in inferior leads, PdW ≥75 ms, MDI ≥0.59 and QWL1) having ≥95% specificity and ≥20% sensitivity in identifying EPI/ENDO origin for PMs. This four-step algorithm identified the origin in 109/115 PMs (95%), 21/24 VTs (88%) in study population and 19/21 VTs (90%) in validation cohort.

Conclusion: Morphologic ECG features that describe the initial QRS vector can help identify basal-superior/lateral EPI VTs in NICM.

Key words: epicardial, ECG criteria, ventricular tachycardia, non-ischemic cardiomyopathy
Published ECG criteria for identifying an epicardial (EPI) origin of ventricular tachycardia (VT) include interval slowing in the initial portion of QRS and morphologic criteria identifying the presence of an unanticipated change in the initial QRS vector. Cut off values for interval criteria have been established primarily in patients without structural heart disease or in those patients with coronary disease. These criteria appear to be region specific and may either not apply or need to be modified to apply to patients with non-ischemic cardiomyopathies (NICM). This is an important consideration since it has been noted that many VTs associated with NICM are epicardial in origin. Furthermore, it has also been previously noted that up to 90% of VTs in NICM originate from substrate-based abnormalities that are located near the superior and lateral peri-valvular aortic and mitral valve region. It would appear therefore that the value of published ECG criteria for identifying an EPI origin must be rigorously assessed in patients with NICM focusing on this peri-valvular region to establish their true accuracy in this important setting. To attempt to accomplish this charge we studied patients with NICM to 1) assess the value of published interval and morphologic criteria for identifying an EPI origin from the basal superior and lateral left ventricle (LV) using a comparison of pacemaps (PM) and VT generated QRS complexes from endocardial (ENDO) versus EPI origin and 2) to determine if a more effective algorithm using modified criteria for identifying an EPI origin in this setting could be established.

Methods

Patient population
Fourteen patients with NICM undergoing ENDO and EPI catheter mapping and ablation for drug refractory ventricular arrhythmias were included in the study. All patients were referred to the Hospital of the University of Pennsylvania for electrophysiological evaluation and catheter ablation. The risks of mapping/ablation were discussed in detail, and all patients gave written informed consent. All procedures were performed following the institutional guidelines of the University of Pennsylvania Health System. In all patients, a decision was made to undergo an EPI ablation because of an unsuccessful ENDO LV ablation before or at the time of the EPI procedure. The diagnosis of NICM was established by LV ejection fraction ≤0.50 and the lack of significant (obstruction >75%) coronary artery disease, prior myocardial infarction, tachycardia-induced cardiomyopathy or primary valvular abnormalities. Epicardial access was obtained using the techniques described by Sosa and colleagues 9,10. An 8F sheath was introduced into the pericardial space, and a 3.5 mm irrigated-tip catheter was advanced through the sheath for activation, pacemapping, and entrainment mapping.

**Substrate mapping**

All patients underwent magnetic electro-anatomical voltage map during basal rhythm as previously described. A three-dimensional anatomical shell of the chamber was constructed and the electrogram signals were displayed as color gradients on a voltage map. Endocardial abnormal voltage was defined by low bipolar voltage (< 1.5 mV) during baseline rhythm (Figure 1). The reference value for defining abnormal electrograms recorded from the LV EPI was recently established based on voltage maps in 8 patients with normal LV 11. Normal EPI electrograms were defined as > 1 mV, which corresponds to 95% of the signals from normal EPI LV recorded at a
distance of at least 1 cm from a defined large coronary vessel. Dense scar was arbitrarily defined as < 0.5 mV for display purposes, and the border zone defined as a transition between scar and normal tissue (0.5 to 1.0 mV in the EPI and to 1.5 mV in the ENDO; Figure 1). Of importance, low electrogram amplitudes have been described around the atrio-ventricular groove as well as surrounding the coronary arteries as a result of the normal distribution of fat tissue in the EPI. However, in contrast to areas of abnormally low voltage and scar, there is normal electrogram morphology demonstrated, defined as lack of electrograms > 80 ms wide, split potentials, or late potentials. Thus the presence of confluent electrogram abnormalities consistent with scar always required the presence of low voltage as well as evidence of > 80 ms wide, split and/or late electrograms. The low voltage area was measured using the area measurement software available on the electroanatomic mapping system (CARTO, Biosense Webster, Diamond Bar, CA). Valvular locations, identified by fluoroscopy and simultaneous bipolar recordings that demonstrated both atrial and ventricular signals of approximately equal amplitude, were tagged and excluded from analysis.

**Pacemapping**

Pacemapping focused on the basal superior and lateral segments of the left ventricle (Josephson sites 8, 10 and 12; Figure 1), in the distribution of confluent scar (Figure 1). PMs at anatomically distinct sites separated by at least 1 cm and representing area of approximately 3-6 cm² from both the ENDO and the EPI surfaces were obtained using bipolar pacing just above the diastolic threshold at cycle length of 400 to 600 ms, using a 3.5 mm irrigated tip catheter (distance between poles = 1 mm), and tagged on an electro-anatomical map (Carto, Biosense Webster,
Diamond Bar, CA). The 12-lead ECG QRS complexes acquired from the PMs were recorded and digitally analyzed off-line using the Prucka Cardiolab recording system (Houston, TX), with high and low pass band width of 0.05 to 100 Hz. Electronic calipers allowing 1-ms resolution were used at a screen velocity of 100 to 200 mm/mV for all measurements.

**Ventricular tachycardia**

We analyzed the 12-lead surface ECG of all the VTs that were demonstrated to originate from the basal superior and lateral LV (Josephson sites 8, 10 and 12; Figure 1). All these VTs had a right bundle-branch block aberrancy and QRS complex predominantly positive in all precordial leads. The VT was defined as originating from the ENDO or EPI region if concealed entrainment with the return cycle length equal to the VT cycle length or a 12 out of twelve ECG lead PM match was observed, and VT was eliminated with catheter ablation.

**Analysis**

The following ECG features were assessed in each PM and VT: (1) QRS duration (QRSd); (2) pseudo-delta wave (PdW), intrinsicoid deflection time (IDT), shortest RS complex (SRS), and maximum deflection index (MDI); (3) presence of q waves in lead I (QWL1), and presence of q wave in inferior leads (Figure 2).

*QRS duration (QRSd)*

The QRSd was defined as the interval measured from the earliest ventricular activation (or from the stimulation artifact) to the offset of the QRS in the precordial leads.

*Pseudodelta wave (PdW)*
The PdW was defined as the interval from the earliest ventricular activation (or from the stimulation artifact) to the onset of the earliest fast deflection in any precordial lead.

Intrinsicoid deflection time (IDT)

IDT was defined as the interval measured from the earliest ventricular activation (or from the stimulation artifact) to the peak of the R wave in V2.

Shortest RS complex (SRS)

SRS was defined as the interval measured from the earliest ventricular activation (or from the stimulation artifact) to the nadir of the first S wave in any precordial lead.

Maximum deflection index (MDI)

MDI was defined as the interval measured from the earliest ventricular activation (or from the stimulation artifact) to the peak of the largest amplitude deflection in each precordial lead (taking the lead with shortest time) divided by the QRSd.

Q or q wave in lead I (QWL1)

A QWL1 was defined as an initial negative deflection, occasionally preceded by a short isoelectric segment of the QRS vector, during VT or paced QRS complex (Figure 3).

Absence of q waves in inferior leads

The absence of q waves in inferior leads was defined as an initial positive deflection of the QRS vector in inferior leads during VT or paced QRS complex (Figure 3).
The analysis of the pacemaps and VTs was performed with the reviewer blinded to the patient number as well as whether the VT was localized to the epicardium or endocardium.

Validation cohort

In order to assess results in a different population we prospectively applied ECG criteria in a second cohort of 11 consecutive patients with NICM undergoing ENDO and EPI catheter mapping and ablation for drug refractory ventricular arrhythmias. In these patients, as with the first group of patients, a decision was made to undergo an EPI ablation because of an unsuccessful ENDO LV ablation before or at the time of the EPI mapping ablation procedure.

Statistical analysis

Categorical variables were compared using a Chi-square except for those with an \( n \leq 5 \) for one or more expected value, for which we used the Fisher’s exact test. Continuous variables (expressed as mean ±SD) were compared using an unpaired Student t-test in case of normal distribution, and a Wilcoxon test in case of non-normal distribution (paired variable). In order to confirm the absence of overweighting from repeated PM measurements from the same subject we reanalyzed our data. A linear mixed model was performed for every variable. Location in the EPI or in the ENDO was considered as a fixed effect predictor in each analyses and each patient was considered as a random effect predictor using a compound symmetrical variance. A P value \( \leq 0.05 \) was considered statistically significant. Sensitivity and specificity were determined for each ECG feature that reached statistical significance in the comparison of ENDO and EPI pacemap QRS complexes.
When the sensitivity and/or specificity was identified as being <75% for any interval measurement from the PM analysis for identifying an EPI or ENDO site of origin we reanalyzed the interval data. Using progressively smaller or larger intervals we attempted to determine if any interval measurement would identify a sensitivity or specificity of at least 75%.

Finally, in an attempt to create a “simple” algorithm that could consistently identify EPI versus ENDO origin using both interval and/or morphology criteria, we attempted to identify criteria with a specificity of ≥95% and a sensitivity of at least 20%. We then applied this algorithm to the entire series of PMs and VTs to determine the ability of the algorithm to identify the EPI versus ENDO origin.

Results

Patient population

Baseline clinical characteristics of the population are shown in Table 1. The study population was composed of 13 men and 1 woman, with an average age of 59 ± 14 years. The average LV ejection fraction was 29 ± 14%. Eleven out of 14 patients had complete ENDO and EPI maps, covering the entire surface of the EPI. In these patients the EPI anatomic voltage maps averaged 458 ± 201 points and the ENDO anatomic voltage maps averaged 277 ± 121 points. The low voltage area was greater in the EPI as compared to the ENDO (56 ± 27 cm² vs. 35 ± 48 cm², respectively, p=0.03). In 2 patients the scar was confined to the EPI, with normal ENDO voltage, while none of the patients had a normal EPI voltage map.

Analysis of Pacemaps
An average of 9 +/- 4 EPI and 6 +/- 4 ENDO PMs were performed per patient. Overall 169 PMs in areas of confluent low voltages from Josephson sites 8, 10 and 12 (102 PMs from the EPI and 67 PMs from the ENDO) were analyzed.

Interval criteria

Epicardial pacing showed longer activation intervals compared to ENDO pacing. There was a significant increase in all the measured intervals with EPI pacing (Figure 4). Interestingly when analyzed with a mixed effects model, differences remained significant for all interval criteria. Mean difference (and 95% confidence interval for difference) between EPI and ENDO were: 29 ms (16 to 42 ms) for QRSd, 24 ms (16 to 31 ms) for PdW, 40 ms (29 to 51 ms) for IDT, 32 ms (17 to 47 ms) for SRS, and 0.14 (0.10 to 0.17) for MDI (p<0.001 for each variable). Importantly, significant overlap existed between EPI and ENDO PMs for most intervals. Therefore, some of these criteria did not reach a high sensitivity and specificity when evaluating PMs from the described basal superior and lateral locations. For both the PdW and the SRS the reported cutoff values (PdW ≥34 ms, SRS ≥121 ms) demonstrated a low specificity (63% and 57% respectively). For the MDI the reported cutoff value of ≥0.55 yielded a good specificity (89%) but a poor sensitivity (30%). Only the IDT with a suggested cutoff value of ≥85 ms was associated with reasonably high sensitivity and specificity values for identifying an EPI origin from the described anatomic sites, 83% and 70% respectively.

Morphology ECG criteria

Most of the EPI paced QRS complexes showed a q wave in lead I compared with the ENDO paced QRS complexes (91% vs. 4%, respectively; p<0.001), yielding
a sensitivity of 91% and a specificity of 96% (Figures 4 and 5). Analysis of the QRS complexes also identified the absence of an initial q wave in leads II, III or aVF (Figure 4) as an indicator of EPI origin (99% vs. 42% in EPI compared to the ENDO, respectively; p<0.001), with a sensitivity of 99% and a specificity of 58%. After performing a mixed effects model analyses significant differences remained (p<0.001) in morphologic criteria, strengthening the observations noted.

**Analysis of Ventricular Tachycardia**

A total of 43 VTs were observed in the 14 patients (Table 2). Thirty-four of the 43 VTs were reproducibly initiated and could be mapped sufficiently to localize the probable exit site of origin to either the EPI or ENDO. Twenty-four VTs (71% of the mapped VTs; 75% of the mapped right bundle branch block morphology VTs) were localized to the basal superior or lateral LV (Josephson sites 8, 10 or 12) and were included in the analysis. Sixteen of these VTs originated from the EPI and 8 from the ENDO. Of these 24 reproducible mapped VTs, 15 were poorly tolerated and were primarily localized based on pacemapping identifying approximate exit sites, and 9 were localized by activation/entrainment mapping targeting isthmus sites for ablation.

**Interval criteria**

The QRSd and the SRS were significantly greater for VTs from the EPI VT group as compared to the ENDO VT group (Figure 6). The rest of the interval measurements (PdW, IDT, and MDI) were not significantly different when comparing VTs originating from the EPI vs ENDO. Previously reported cut off values for PdW, IDT, and SRS interval criteria tended to lack specificity in identifying EPI origin for
VTs (specificity was ~ 50% for all three measurements). The MDI was found to have a specificity of 75% but lacked sensitivity (33%) for the diagnosis of VT originating from the EPI from the described superior basal and lateral LV in patients with NICM.

Morphology criteria

Importantly, the presence of a q wave in lead I reached a sensitivity and specificity of 88% (p<0.001) for predicting an EPI origin of the VT from the basal superior and lateral LV. The absence of q waves in inferior leads also emerged as a very sensitive feature identifying an EPI origin (94%; p=0.09) for VT (Figures 2, 6 and 7).

Revised Interval Criteria

In order to achieve more accurate diagnosis for the origin of the PMs from the EPI vs. the ENDO when using interval criteria, we identified those cutoffs for each variable that were able to achieve sensitivity and specificity of ≥75%. A 75% level of accuracy was only observed with cutoffs’ modifications for the MDI and IDT. The decrease of the cutoff for MDI from ≥ 0.55 to ≥ 0.45 increased the sensitivity for the diagnosis of EPI origin from 30% to 76% with a slight decrease in the specificity (from 89 to 75%). Similarly raising the cutoff for IDT from ≥ 85 ms to ≥ 90 ms, increased the specificity for the diagnosis of EPI PM origin from 70% to 79% with a slight decrease in the sensitivity (from 83 to 76%). Using these revised cutoff values for the VTs, we demonstrated a sensitivity and specificity of 63% and 38% for MDI and 56% and 67% for IDT in identifying the ENDO versus EPI VT origin in the setting of NICM.
Combined Criteria and a New ECG Algorithm

Given the limitations observed when using the individual interval criteria for the diagnosis of PM or VT originating from the EPI in patients with NICM we sought to create a multistep algorithm that might optimize recognition of the site of origin. We began by identifying those cutoffs for interval criteria that were able to achieve a high specificity of $\geq 95\%$ with a sensitivity of $\geq 20\%$ for identifying a paced QRS VT like complex from the EPI. These criteria included interval criteria of $\text{PdW} \geq 75\text{ ms}$ and $\text{MDI} \geq 59\text{ ms}$. We then evaluated a new 4 step algorithm combining the defined morphology criteria (presence of q wave in inferior leads and presence of q wave in lead I) with the interval criteria. The criteria were applied in the sequence shown (Figure 8). This simple 4-step algorithm reached a high sensitivity and specificity (Figure 8) for correctly identifying the origin of 109 out of 115 PMs (96% sensitivity and 93% specificity for EPI origin) and 21 out of 24 VTs (88% sensitivity and 88% specificity for EPI origin).

Validation cohort

Baseline clinical characteristics of the validation population were similar to the original cohort (9 men and 2 woman, average age of 56 ±20 years and average LV ejection fraction of 35 ±8%). In these patients 21 of 32 (66%) mapped VTs and 21 of 29 (72%) mapped VTs with a right bundle branch block morphology originated from a basal superior or lateral origin (segments 8, 10 and 12 of Josephson) using standard mapping localization techniques with 14 epicardial versus 7 endocardial in origin. The new ECG algorithm applied to this validation population correctly identified the origin in 19 out of 21 VTs (93% sensitivity and 86% specificity for EPI origin).
Discussion

This study determined prospectively the value of previously published interval and morphology ECG criteria for identifying an EPI VT site of origin in patients with NICM. We centered our attention on the basal anterior or superior and lateral region of the LV because the gross anatomic changes in those regions most commonly serve as the substrate for VT in this setting. Furthermore, the focus on this important anatomic region permitted a sufficient number of VTs to be identified and detailed pacemapping to be performed so that a meaningful comparison of ENDO versus EPI QRS morphologies could be made. The results unequivocally show that the morphologic criteria (presence of a q wave in lead I and absence of q waves in the inferior leads) appear to be the most specific criteria, and in the case of presence of a QWL1 also a very sensitive criterion for identifying an EPI site of origin of all prior published criteria. The presence of a QWL1 is a marker of the initial rightward activation of the LV base from the EPI origin. Pacemap ECGs in patients with NICM demonstrated a QWL1 almost uniformly from the EPI compared to the ENDO (91 vs 4%, p <0.001). The value of an initial QWL1 was confirmed as a valuable diagnostic feature with a sensitivity of 88% and a specificity of 88% for the diagnosis of the origin of the 24 VTs localized to the basal superior and lateral LV in the same patients.

Previously published interval criteria that identify slow conduction in the initial portion of the QRS were not as reliable for consistently identifying the ENDO versus EPI origin in the setting of NICM, despite their proven value in patients without structural heart disease or with coronary disease. Only the IDT appeared to...
have significant localizing value in this setting, but with lower sensitivity (83%) and specificity (70%) values than previously reported in patients with coronary artery disease. We have previously documented that published interval criteria suggesting an EPI VT origin do not seem to be equally accurate among all LV regions. All of these interval criteria are based on the widening that occurs in the initial part of the QRS when the VT originates from the EPI. Of note, these differences in the initial slowing of the QRS between ENDO and EPI sites will be exaggerated when ENDO sites are closer to the septum and in proximity to the Purkinje network. Furthermore, differences in the initial versus total QRS as indexed by the MDI and other interval criteria will be muted as one moves laterally with the overall duration of the QRS complex increasing. Of note, one can improve the specificity of the IDT by raising the cut off to 90 ms from 85 ms without a dramatic loss of sensitivity. Furthermore, the sensitivity of the MDI can be improved by lowering the ratio cutoff to 0.45 from 0.55. The study confirmed that these revisions in the cutoff values improve the predictive value of the IDT and MDI intervals but they still do not match the predictive value of the simple morphologic criteria for identifying an EPI origin in this setting.

**New ECG algorithm for localizing VT in patients with NICM**

Given the potential limitations observed when using individual criteria for the diagnosis of PMs or VTs originating from the EPI in patients with NICM, we sought to create a simple but multistep algorithm that might further optimize recognition of the site of origin and incorporate both interval and morphology criteria. We used the two morphology criteria and adjusted interval criteria that were able to achieve a high specificity of ≥95% with a sensitivity of at least 20% for identifying a paced QRS VT like complex from the EPI. The criteria and their sequence of evaluation included:
presence of q waves in inferior leads, a PdW >75 ms, a MDI ≥0.59, and the presence of a q wave in lead I (Figure 8). Using this algorithm 109 out of 115 PMs (95%) and 21 out of 24 VTs (88%) were correctly identified. Then we applied the algorithm to a different prospective population of patients with NICM in order to assess its value, and 19 out of 21 VTs (90%) were correctly identified with respect to an epicardial versus endocardial origin. Whether this suggested algorithm would enhance the value of the single morphologic criteria alone remains to be determined with certainty. It is hopeful that this algorithm can be used in equivocal situations when such confirmation of an EPI VT origin is critical for patient management.

Limitations

This investigation focused only on patients who had NICM and only on the region of the LV that most frequently demonstrates the substrate for VT, i.e., the basal anterior, antero-lateral, and lateral LV ENDO and EPI. We did this to enhance the power of the investigative effort and to facilitate the collection of ENDO versus EPI comparative data in areas that typically demonstrate substrate voltage abnormalities. Admittedly, a very small portion of our mapped VTs (29%) and even smaller portion of mapped VTs with a right bundle branch block morphology (22%) originated from other anatomic sites such as the basal inferior LV. We acknowledge that because of the site/region-specific nature of EPI morphologic criteria, the criteria described cannot be applied to other regions. However, given the frequency of VTs from the basal anterior and lateral LV in patients with NICM and the ability of the ECG precordial transition to readily identify the basal LV VTs to which the criteria should apply our data should have significant clinical merit.
A relatively modest number of VTs were included -24 morphologically distinct VTs in the study group and 21 morphologically distinct VTs in the validation group- to which the ECG morphologic criteria were applied and evaluated. Of note, we included only those in which detailed activation, entrainment and/or pacemapping identified the specific ENDO or EPI location. Importantly, the effectiveness of the criteria for localizing the ENDO versus EPI PMs and the strong correlation between the PM findings and the observations during the VTs support the validity of the observation.

The pacing threshold varied from <1.0 mA to 20 mA and the precise value was not recorded as part of the protocol for each pacing site. Importantly, we did pace at threshold values that produced consistent capture in order to have a standardized protocol.

**Clinical implications**

Patients with NICM frequently have an EPI origin for VT. Because an EPI ablation procedure requires a different level of risk and resources, it is imperative to identify which patients are likely to benefit from an EPI approach with their initial procedures. The study results strongly suggest that simple morphologic criteria including the presence of a q wave in lead I, create a high degree of suspicion for a probable EPI location in the setting of NICM. A suggested four-step algorithm that incorporates modified interval criteria and well-defined morphologic criteria enhances the diagnostic sensitivity and specificity of ECG assessment for VT localization. These results should facilitate the planning and success of catheter ablation of VT in this setting. Of note, the algorithm was developed for patients with NICM focusing on the LV region that serves as the most common region of VT origin and it should not
be considered useful for VTs from other regions of the left ventricle or for other types of cardiac disease.

**Conflict of Interest Disclosures:** None.

**References**


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ENDO: Encocardial; EPI: Epicardial; F: Female; ICD: Implantable cardiac defibrillator; LVEF: Left ventricle ejection fraction; M: Male; NICM: Non-ischemic left ventricle cardiomiopathy; N: No; RM: Regional Map; Y: Yes.
Table 2. Localization on VTs

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ENDO: Endocardial; EPI: Epicardial; Sites refer to the schematic representation by Josephson.
Figure Legends

Figure 1. **Panel A**: A left posterior oblique view of a bipolar ENDO voltage map in sinus rhythm shows the typical distribution of low voltage (<1.5 mV) abnormalities around the mitral annulus. **Panel B**: A left posterior oblique view of a bipolar EPI voltage map in sinus rhythm from another patient also showing low voltage (<1.0 mV) abnormalities on the epicardium in proximity to the mitral valve. The electrograms were not only low in amplitude but were also typically fractionated and late. The perivalvular superior and lateral regions of the endocardial and epicardial LV (Josephson sites 8, 10, 12) characteristically demonstrated the abnormal substrate and were the regions of origin of most VTs and focus of detailed pacemapping. (See text for details).

Figure 2. QRS from ENDO VT showing discrepancy between interval and morphology criteria. This example demonstrates all interval and morphology criteria routinely assessed. The QRS from VT with ENDO site of origin in the example shown demonstrates interval criteria suggesting EPI VT, but morphology criteria (absence of a q wave in lead I and presence of small q waves in inferior leads) supporting an ENDO origin.

Figure 3. Schematic representation showing suggested basis for morphologic differences in QRS in lead I and aVF based on initial regional (small arrow) followed by global LV activation (large arrows) from endocardial versus epicardial VT origin from superior-lateral LV. In **Panel A**, a VT origin from the endocardium shows small q waves in inferior leads and small r wave in lead I representing the small segment of myocardium that depolarizes with an ENDO to EPI activation before the main activation wave front proceeds from a superior to inferior and left to right direction. **In contrast in Panel B** a VT origin from the epicardium will not show an initial q wave in the inferior leads and will consistently show a q wave in lead I as initial activation is more consistent with the net vector of the global activation pattern from left to right and superior to inferior.
Figure 4. QRS morphology and interval values for ENDO and EPI PMs from basal superior and lateral LV sites in patients with NICM. Each interval measurement (the five top variables in the figure) was observed to be longer from the EPI than from the ENDO. However, the sensitivity/specificity values (right box) using the reported cutoffs for interval criteria were limited. The presence of a q wave in lead I was nearly uniformly identified on EPI PMs and was also noted to be highly specific criteria. Ave: average; ENDO: endocardium; EPI: epicardium; IDT: intrinsicoid deflection time; MDI: maximum deflection index; PdW: pseudo-delta wave; SRS: shortest RS complex; std dev: standard deviation.

Figure 5. Morphologic features suggesting EPI versus ENDO origin during pacemapping in basal superior and lateral LV in patients with NICM. Panels A and B show PMs from superior basal and lateral basal ENDO LV, respectively. The absence of q waves in lead I and the presence of q waves in inferior leads are noted. Panels C and D show PMs performed from superior basal and superior-lateral basal regions in the directly opposite EPI LV. Previously seen q waves in inferior leads are not observed and lead I shows q waves. Blue arrows show inferior q waves with ENDO pacing. Red arrows show q waves in lead I with EPI pacing.

Figure 6. QRS morphology and interval values for ENDO and EPI VT from basal superior and lateral LV sites in patients with NICM. Only the QRSd and the SRS complex duration were observed to be significantly longer from the EPI than from the ENDO. The rest of the interval criteria measurements were not significantly different when comparing EPI and ENDO origin. The sensitivity/specificity values (right box) for interval criteria using the reported cutoffs were poor for identifying VT site of origin. Both morphology criteria showed a very high sensitivity, and the presence of a q wave in lead I was also seen to be a specific criterion for identifying the VT site of origin. Ave: average; ENDO: endocardium; EPI: epicardium; IDT: intrinsicoid deflection time; MDI: maximum deflection index; PdW: pseudo-delta wave; QRSd: QRS duration; SRS: shortest RS complex; std dev: standard deviation.

Figure 7. Twelve-lead ECG showing characteristic morphologic features of VT originating from epicardium versus endocardium. ECG tracings A to E show 5 VTs
arising from different EPI superior and lateral basal origins. **Red arrows** point out q waves in lead I, representing the initial rightward activation from the EPI to the ENDO. **ECG tracings F to I** show 4 VTs arising from the opposite ENDO location for comparison. There is no q wave in lead I as the initial activation goes leftward from ENDO to EPI. **Blue arrows** point out small q waves in inferior leads, representing the initial superiorly directed activation from the ENDO to EPI.

Figure 8. Four-step algorithm for identifying EPI origin from basal superior and lateral LV in the setting of NICM. The three top steps have a high specificity and the last step is the most accurate. The total sensitivity and specificity of the algorithm in the study population for PM localization reach 96 and 93%, respectively.
Absence of q wave

Presence of q wave

QRS: 206 ms
Pseudo-delta: 56 ms
MDI: 103 ms/206 ms: 0.5
Shortest RS: 157 ms

IDT: 112 ms
**QRS duration** (ave ms ± std dev)
- **ENDO:** 170 ± 19 ms
- **EPI:** 232 ± 47 ms
  - **P = 0.002**

**Pseudo-delta wave** (ave ms ± std dev)
- **ENDO:** 34 ± 13 ms
- **EPI:** 48 ± 28 ms
  - **P = 0.1**

**Intrinsicoid deflection time** (ave ms ± std dev)
- **ENDO:** 85 ± 20 ms
- **EPI:** 108 ± 41 ms
  - **P = 0.1**

**Shortest RS complex** (ave ms ± std dev)
- **ENDO:** 119 ± 23 ms
- **EPI:** 159 ± 43 ms
  - **P = 0.008**

**Maximum deflection index** (ave % ± std dev)
- **ENDO:** 50 ± 10 ms
- **EPI:** 46 ± 13 ms
  - **P = 0.3**

**Presence of a q wave in lead I (%)**
- **ENDO:** 12%
- **EPI:** 88%
  - **P < 0.001**

**Absence of q waves in inferior leads (%)**
- **ENDO:** 37%
- **EPI:** 94%
  - **P = 0.09**

**PdW ≥ 34 ms**
- **SN 62% & SP 50%**

**IDT ≥ 85 ms**
- **SN 69% & SP 50%**

**SRS ≥ 121 ms**
- **SN 93% & SP 50%**

**MDI ≥ 55**
- **SN 33% & SP 75%**

**q in lead I**
- **SN 88% & SP 88%**

**No q in inf. leads**
- **SN 94% & SP 63%**