ECG Criteria to Identify Epicardial Ventricular Tachycardia in Nonischemic Cardiomyopathy

Ermengol Vallès, MD; Victor Bazan, MD; Francis E. Marchlinski, MD

Background—ECG criteria identifying epicardial (EPI) origin for ventricular tachycardia (VT) in nonischemic cardiomyopathy 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 pace maps in 14 patients with nonischemic cardiomyopathy. Pace mapping focused on low bipolar voltage areas. Published morphology criteria: q wave in lead I (QWL1) and no q waves in inferior leads and interval criteria: pseudo-delta wave ≥34 ms, intrinsicoid deflection time ≥85 ms, shortest RS complex ≥121 ms, and maximum deflection index ≥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 pace maps (91% versus 4%; P<0.001), identified 14 of 16 EPI VTs (sensitivity, 88%), and was seen in 1 of 8 ENDO VTs (specificity, 88%). None of the remaining criteria achieved similar sensitivity without specificity <50%. We identified 4 criteria (q waves in inferior leads, pseudo-delta wave ≥75 ms, maximum deflection index ≥0.59, and QWL1) having ≥95% specificity and ≥20% sensitivity in identifying EPI/ENDO origin for pace maps. This 4-step algorithm identified the origin in 109 of 115 pace maps (95%), 21 of 24 VTs (88%) in the study population, and 19 of 21 VTs (90%) in validation cohort.

Conclusions—Morphological ECG features that describe the initial QRS vector can help identify basal-superior/lateral EPI VTs in nonischemic cardiomyopathy. (Circ Arrhythm Electrophysiol. 2010;3:63-71.)

Key Words: epicardial • ECG criteria • ventricular tachycardia • nonischemic cardiomyopathy

Published ECG criteria for identifying an epicardial (EPI) origin of ventricular tachycardia (VT) include interval slowing in the initial portion of QRS and morphological criteria identifying the presence of an unanticipated change in the initial QRS vector.1-4 Cutoff values for interval criteria have been established primarily in patients without structural heart disease or in those patients with coronary disease.3,4 These criteria appear to be region specific and may either not apply or need to be modified to apply to patients with nonischemic cardiomyopathies (NICM).2 This is an important consideration because it has been noted that many VTs associated with NICM are epicardial in origin.5,6 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 perivalvular aortic and mitral valve region.7,8 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 perivalvular 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 morphological criteria for identifying an EPI origin from the basal superior and lateral left ventricle (LV) using a comparison of pace maps and VT-generated QRS complexes from endocardial (ENDO) versus EPI origin and (2) determine whether a more effective algorithm using modified criteria for identifying an EPI origin in this setting could be established.

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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 \( \leq 0.50 \) 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 et al. An 8F sheath was introduced into the pericardial space, and a 3.5-mm irrigated-tip catheter was advanced through the sheath for activation, pace mapping, and entrainment mapping.

**Substrate Mapping**

All patients underwent magnetic electroanatomic voltage map during basal rhythm as previously described. A 3D anatomic 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 \( (<1.5 \text{ mV}) \) 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. Normal EPI electrograms were defined as \( >1 \text{ mV} \), 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 \( <0.5 \text{ mV} \) for display purposes, and the border zone was defined as a transition between scar and normal tissue \( (0.5 \text{ to } 1.0 \text{ mV in the EPI and to } 1.5 \text{ mV in the ENDO; Figure 1}) \). Of importance, low electrogram amplitudes have been described around the atrioventricular 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 electro-

**Figure 1.** A, Left posterior oblique view of a bipolar ENDO voltage map in sinus rhythm shows the typical distribution of low voltage \( (<1.5 \text{ mV}) \) abnormalities around the mitral annulus. B, Left posterior oblique view of a bipolar EPI voltage map in sinus rhythm from another patient also showing low-voltage \( (<1.0 \text{ mV}) \) 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 pace mapping.

**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.
grams >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, Calif). 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.

**Pace Mapping**

Pace mapping 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). Pace maps at anatomically distinct sites separated by at least 1 cm and representing area of approximately 3 to 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 electroanatomic map (CARTO, Biosense Webster). The 12-lead ECG QRS complexes acquired from the pace maps were recorded and digitally analyzed off-line using the Prucka Cardiolab recording system (Houston, Tex), with high- and low-pass bandwidth 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 of 12-ECG lead pace map match was observed, and VT was eliminated with catheter ablation.

**Analysis**

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

**QRS Duration**

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.

**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.

**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.

**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.

**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.

**QWL1**

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 pace maps 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**

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 \( \chi^2 \) test except for those with \( n \leq 5 \) for 1 or more expected values, for which we used the Fisher exact test. Continuous variables (expressed as mean \pm SD) were compared using an unpaired Student \( t \) test in the case of normal distribution and a Wilcoxon test in case of nonnormal distribution (paired variable). To confirm the absence of overweighting from repeated pace map 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 symmetry variance. A probability value \( P \leq 0.05 \) was considered statistically significant. Sensitivity and specificity were determined for each ECG feature that reached statistical significance in the comparison of ENDO and EPI pace map QRS complexes.

When the sensitivity and/or specificity was identified as being <75\% for any interval measurement from the pace map 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 whether any interval measurement would identify a sensitivity or specificity of \( \geq 75\% \).

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 \( \geq 95\% \) and a sensitivity of \( \geq 20\% \). We then applied this algorithm to the entire series of pace maps 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 \pm 14 years. The average LV ejection fraction was 29 \pm 14\%. Eleven 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 \pm 201 points and the ENDO anatomic voltage maps averaged 277 \pm 121 points. The low voltage area was greater in the EPI as compared with the ENDO (56 \pm 27 cm\(^2\) versus 35 \pm 48 cm\(^2\), respectively, \( P=0.03 \)). In 2 patients, the scar was confined to the EPI, with normal ENDO voltage, whereas none of the patients had a normal EPI voltage map.

Analysis of Pace Maps

An average of 9 \pm 4 EPI and 6 \pm 4 ENDO pace maps were performed per patient. Overall, 169 pace maps in areas of confluent low voltages from Josephson sites 8, 10 and 12 (102 pace maps from the EPI and 67 pace maps from the ENDO) were analyzed.

Interval Criteria

Epicardial pacing showed longer activation intervals compared with 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 intervals 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 pace maps for most intervals. Therefore, some of these criteria did not reach a high sensitivity and specificity when evaluating pace maps from the described basal superior and lateral locations. For both the PdW and the SRS, the reported cutoff values (PdW \( \geq 34 \) ms, SRS \( \geq 121 \) ms) demonstrated a low specificity (63\% and 57\%, respectively). For the MDI, the reported cutoff value of \( \geq 0.55 \) yielded a good specificity (89\%) but a poor sensitivity (30\%). Only the IDT with a suggested cutoff value of \( \geq 85 \) 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\% versus 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% versus 42% in EPI compared with the ENDO, respectively; \( P < 0.001 \)), with a sensitivity of 99% and a specificity of 58%. After performing mixed-effects model analyses, significant differences remained \( (P < 0.001) \) in morphological criteria, strengthening the observations noted.

**Analysis of VT**

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 pace mapping 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 with 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 versus ENDO. Previously reported cutoff values for PdW, IDT, and SRS interval criteria tended to lack specificity in identifying EPI origin for VTs (specificity was ≈50% for all 3 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**

To achieve more accurate diagnosis for the origin of the pace maps from the EPI versus 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 cutoff 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 pace map 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 pace map or VT origin,

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Sites refer to the schematic representation by Josephson.

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 indicates average; std dev, standard deviation.
nating 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 ≥95% with a sensitivity of ≥20% for identifying a paced QRS VT-like complex from the EPI. These criteria included interval criteria of PdW ≥75 ms and MDI ≥59 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 of 115 pace maps (96% sensitivity and 93% specificity for EPI origin) and 21 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 women; average age, 56±20 years; average LV ejection fraction, 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 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 pace mapping to be performed so that a meaningful comparison of ENDO versus EPI QRS morphologies could be made. The results unequivocally show that the morphological 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
New ECG Algorithm for Localizing VT in Patients With NICM

Given the potential limitations observed when using individual criteria for the diagnosis of pace maps 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 2 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 of 115 pace maps (95%) and 21 of 24 VTs (88%) were correctly identified. We then applied the algorithm to a different prospective population of patients with NICM to assess its value, and 19 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 morphological criteria alone remains to be determined with certainty. It is hoped that this algorithm can be used in equivocal situations when such confirmation of an EPI VT origin is critical for patient treatment.

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, that is, 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 morphological 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 morphological criteria were applied and evaluated. Of note, we included only those in which detailed activation, entrainment, and/or pace mapping identified the specific ENDO or EPI location. Importantly, the effective-
ness of the criteria for localizing the ENDO versus EPI pace maps and the strong correlation between the pace map 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 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 morphological 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 4-step algorithm that incorporates modified interval criteria and well-defined morphological 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 LV or for other types of cardiac disease.

Disclosures
None.

References

CLINICAL PERSPECTIVE
ECG criteria for identifying an epicardial origin of ventricular tachycardia appear to be region and substrate specific. This is an important consideration because many ventricular tachycardias associated with nonischemic cardiomyopathy are epicardial in origin and most of them originate from substrate-based abnormalities near the superior and lateral mitral valve region. It is imperative to identify which patients are likely to benefit from an epicardial approach. Simple morphological criteria, including the presence of a q wave in lead I, create a high degree of suspicion for a probable epicardial location in the setting of nonischemic cardiomyopathy. A suggested 4-step algorithm that incorporates modified interval criteria and well-defined morphological criteria enhances the diagnostic sensitivity and specificity of ECG assessment for ventricular tachycardia localization and should facilitate the planning and success of catheter ablation of ventricular tachycardia in this setting.
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