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Ultra-High-Frequency ECG-Derived Local Depolarization Duration as a Potential Digital Biomarker of Myocardial Scar in Dilated Cardiomyopathy

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Title: Ultra-High-Frequency ECG-Derived Local Depolarization Duration as a Potential Digital Biomarker of Myocardial Scar in Dilated Cardiomyopathy

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Karol Curila and Pavel Leinveber are among the inventors of the U.S. patent 11,517,243 B2, titled 'Method of Electrocardiographic Signal Processing and Apparatus for Performing the Method,' and are shareholders of VDI Technologies.

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Abstract

Myocardial scarring, detected by late gadolinium enhancement (LGE) on cardiac magnetic resonance (CMR) imaging, is associated with sudden cardiac death in dilated cardiomyopathy (DCM). Ultra-high-frequency electrocardiography (UHF-ECG) characterizes local ventricular activation and may reveal electrical disturbances associated with myocardial scarring. We investigated the relationship between UHF-ECG-derived local depolarization duration and LGE presence and extent in a prospective multicentre cohort of 87 patients with DCM. Mean local depolarization duration across leads V1–V6 was compared with CMR findings, with analyses stratified by QRS duration and morphology. In patients with narrow QRS complexes (n=34) or intraventricular conduction delay (n=23), longer mean local depolarization duration correlated with greater LGE extent (ρ=0.559 and 0.473, respectively). In these subgroups, local depolarization duration also discriminated between patients with and without LGE. No significant association with LGE presence was observed in the overall cohort or in patients with left bundle branch block. These findings suggest that the relationship between local depolarization duration and myocardial scarring may depend on QRS characteristics. UHF-ECG-derived local depolarization duration may serve as a digital biomarker of myocardial scarring in selected patients with DCM, although these exploratory findings require independent validation.

Keywords: ultra-high-frequency ECG, cardiac magnetic resonance imaging, late-gadolinium enhancement, local depolarization duration, digital biomarker

Abbreviations:

CMR - cardiac magnetic resonance imaging
DCM – dilated cardiomyopathy
ICD – implantable cardioverter-defibrillator
LGE – late-gadolinium enhancement
LVEF– left ventricular ejection fraction
mVd – mean local depolarization duration
SCD – sudden cardiac death
UHF-ECG – ultra-high-frequency electrocardiography
UHFQRS – ultra-high-frequency QRS complex

Introduction

The risk of sudden cardiac death (SCD) due to ventricular arrhythmias is not solely limited to patients with a left ventricular ejection fraction (LVEF) less than 35%[1]; ICD implantation should be considered even in patients with an LVEF greater than 35% if they have multiple risk factors associated with ventricular arrhythmias and SCD[2]. The presence of late-gadolinium enhancement (LGE) on cardiac magnetic resonance imaging (CMR) is one of the potential additional SCD risk-modifying factors in patients with DCM[1,3]. CMR is the non-invasive gold standard method for quantifying myocardial scar. However, because of operational constraints[4] and limited availability[5], timely access to CMR may be restricted in some healthcare settings. Therefore, there is a clear need for a simple, non-invasive tool that may help prioritize patients for CMR.

Ultra-high-frequency electrocardiography (UHF-ECG) is an emerging digital electrophysiological technology involving a broadband 14-lead ECG utilizing ultra-high frequencies of 150-1000 Hz[6]. These oscillations, located in the ultra-high-frequency QRS complex (UHF-QRS), are generated by the rapid sodium current–driven membrane potential gradient during phase 0 of the myocardial action potential[6]. Processing of ultra-high frequencies in each of the ECG precordial leads supports spatiotemporal assessment of ventricular electrical activation.

UHF-ECG enables the assessment of local depolarization duration (Vd), defined as the time duration measured at half of the UHF-QRS complex amplitude in each lead (*Figure 1*). Therefore, Vd provides a quantitative measure reflecting local ventricular depolarization and conduction, with low values indicating more rapid conduction and high values indicating prolonged local depolarization[7]. Importantly, Vd provides an automatically derived quantitative ECG parameter rather than relying solely on visual interpretation of QRS morphology.

It is exceedingly straightforward to apply, as it utilizes the same electrodes as a standard ECG (*Figure 1*) while providing significantly more information on the UHF-QRS morphology than can be discerned from a QRS pattern on a standard ECG[6]. In the past few years, UHF-ECG has been primarily implemented in studies related to cardiac resynchronization[8] therapy and conduction system pacing[9,10]. However, whether quantitative parameters derived from UHF-ECG can serve as digital biomarkers of myocardial structural abnormalities remains unclear.

We therefore aimed to investigate whether UHF-ECG-derived local depolarization duration is associated with the presence and extent of CMR-detected myocardial scar and to evaluate its potential as a digital biomarker of myocardial scar in patients with DCM.

Methods

Study Design and Study Population

This prospective cohort study included 89 patients diagnosed with DCM or hypokinetic non-dilated cardiomyopathy (HNDCM) via CMR at two hospitals (Semmelweis University, Budapest, and St. Anne's University Hospital, Brno) in 2023-2025. HNDCM patients were included in the study since they were recognized as a spectrum of DCM[11]. DCM was diagnosed based on reduced LVEF (LVEF < 50%) and elevated left ventricular end-diastolic volume indexed to body surface area (LVEDVi)[12] corrected for sex, body size, and age[13]. HNDCM was defined as global systolic dysfunction of the left ventricle, or both the left and right ventricles, defined by LVEF < 45% measured by CMR, which was not caused by abnormal loading conditions or coronary artery disease[11]. Patients with other cardiomyopathies, congenital heart disease, or with subendocardial LGE at CMR were excluded from our trial.

At the time of enrolment, all patients underwent a 10-minute UHF-ECG recording using standardized Mason-Likar lead positions (*Figure 1*).

The study was conducted in compliance with the principles outlined in the Declaration of Helsinki. Informed consent was provided by all patients. The trial was approved by the local ethics committees (Semmelweis University, Budapest: BMEÜ/726-4/2022/EKU, St. Anne's University Hospital: 11V/2021).

Cardiac MRI

All patients underwent CMR imaging using a 1.5 Tesla MRI scanner (either a Siemens Magnetom Aera or a Philips Ingenia). Cine images were attained in the conventional short-axis and long-axis views (balanced steady-state free precession bSSFP images). LGE images in the same views as cine images were acquired using a segmented inversion recovery sequence 10-15 minutes after administration of an intravenous bolus of 0.15 mmol/kg gadolinium contrast agent (gadobutrol, Gadovist), with an infusion rate of 2-3 ml/sec. The inversion time was set to enable optimal nulling of the normal myocardium.

Postprocessing was performed using Medis Suite Software (Medis Medical Imaging Software, The Netherlands) by a CMR specialist with European Association of Cardiovascular Imaging Level III accreditation, blinded to the UHF-ECG data. Volumetric parameters assessed from the short-axis cine images using standard techniques included LVEF, left ventricular mass index (LVMi), left ventricular end-systolic volume indexed to body surface area (LVESVi), and LVEDVi. Semi-automated scar quantification was performed on short-axis images using endo- and epicardial contouring. LGE quantification was performed using the FWHM technique (threshold of 50% of the maximum intensity within the scar). In cases with artifacts present in the myocardium, manual correction was performed. LGE volume was expressed in grams. LGE extent (LGE%) was defined as the percentage of LV mass comprised by LGE volume. LGE – was defined by the absence; LGE+ was defined by the presence of LGE regardless of LGE%.

Ultra-High-Frequency ECG

A ventricular dyssynchrony imaging (VDI) monitor (*ISI Brno, Cardion, FNUSA, Czech Republic*) was used to record UHF-ECG for 10 minutes in a resting supine position using 14 leads with eight precordial electrodes. ECG signals were recorded at a sampling rate of 5 kHz with a bandwidth of 1.5 kHz. Data were analyzed using VDI Scientific software (*VDI Technologies Inc., Brno, Czech Republic*). For each precordial lead, normalized median-amplitude envelopes were generated by gating and averaging all analyzable heartbeats recorded during UHF-ECG acquisition in each of 16 frequency bands, covering the frequency range from 150 to 1000 Hz. The UHF-QRS complex was generated by averaging the 16 normalized median-amplitude envelopes and was displayed as a color map for each lead (*Figure 1*). Vd was calculated as the duration of the UHF-QRS complex measured at 50% of its peak amplitude in each precordial lead. The average of Vd from lead V1 to V6 (mVd V1-V6) was used for further analysis. Signal processing and Vd calculation were performed automatically, yielding a quantitative ECG-derived parameter.

Subgroup analysis according to QRS complex width and QRS morphology

The VDI Scientific (*VDI Technologies Inc., Brno, Czech Republic*) was used to automatically measure QRS complex durations. Subgroup analysis was performed according to QRS complex width and QRS morphology. Narrow QRS was defined as QRS<120 ms, and wide QRS as QRS≥120 ms. In patients with wide QRS complexes, further analysis was performed based on QRS complex morphology. Left bundle branch block (LBBB) was defined according to the Strauss criteria[14]. Right bundle branch block (RBBB) was identified by a QRS duration ≥ 120 ms, with an rR' pattern in V1 and a wide S wave in lead I[15]. QRS complexes in the wide QRS group that did not meet criteria for complete or incomplete bundle-branch block were classified as intraventricular conduction delay (IVCD).

Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics for Windows, Version 29.0.1.0 (*Armonk, NY: IBM Corp.*) and GraphPad Prism Version 9.1.2 (*GraphPad Software, La Jolla, CA, USA*). The distribution of continuous variables was evaluated using the Shapiro–Wilk test, indicating that none of the variables were normally distributed. Consequently, continuous variables are presented as median [interquartile range (IQR)], and comparisons between groups were performed using the Mann–Whitney U test. Categorical variables are reported as counts (percentages) and were compared utilizing $\chi 2$ or Fisher's exact test, as appropriate. Spearman's rho correlation was used to evaluate the correlation between continuous UHF-ECG and CMR measurements. A Receiver Operating Characteristic (ROC) analysis was conducted to evaluate the diagnostic performance of mVd V1-V6 in distinguishing between patients with and without LGE. To formally assess whether QRS width modified the association between mVd V1–V6 and LGE presence, binary logistic regression was performed including mVd V1–V6, QRS complex width subgroup (QRS<120 vs. QRS≥120 ms), and their interaction term, with adjustment for age and sex. Differences were considered statistically significant at the two-sided $p < 0.05$ level.

Results

Baseline characteristics

After a thorough evaluation, two patients were excluded due to the presence of subendocardial LGE, referring to ischemic etiology. Consequently, eighty-seven patients were included in the final analysis. UHF-ECGs were obtained at the time of the cardiac MRI assessment in most cases (median 0 days [IQR: 0.0-28.0]). The baseline characteristics of the cohort are summarized in *Table 1*. The majority of participants were men (77.0%), and the median age of the cohort was 56.0 years (IQR: 48.0-68.0). Thirty-four patients had narrow QRS complexes, and over half of the cohort had LGE on their CMR images. The median mVd V1-V6 was 52.0 ms (IQR: 44.2-66.8) in the whole patient cohort. Patients with QRS≥120 ms were older and had

a higher incidence of mineralocorticoid receptor antagonist treatment, along with an increased prevalence of heart failure and diabetes mellitus (*Table 1*). Additionally, LVEF was significantly lower in patients with wide QRS complexes; all other left ventricular MRI parameters and LGE burden remained consistent across the different patient subgroups according to QRS width (*Table 2*).

CMR and UHF-ECG correlation in the full cohort and by QRS complex width

We found no correlation between LGE% and mVd V1-V6 in the overall cohort (ρ=0.102, p=0.346). The median mVd V1-V6 was 49.5 ms (IQR: 38.4-74.7 ms) in LGE- patients compared to 52.1 ms (IQR: 46.8-62.3 ms) in LGE+ patients (p = 0.351). The mVd V1-V6 duration was longer in patients with QRS≥120 ms (median: 62.3 ms, [IQR: 52.4-77.8 ms]), compared to the QRS<120 ms subgroup (median: 43.9 ms, [IQR: 39.0-47.5 ms]) (p<0.001).

In patients with narrow QRS, UHF-ECG measurements showed significantly increased mVd V1-V6 in those with LGE than in those without the presence of LGE (*Figure 2*). However, mVd V1-V6 did not differ between patients with or without LGE in the QRS≥120ms subgroup (*Figure 2*).

Consistent with these subgroup findings, a significant interaction between mVd V1–V6 and QRS complex width category was observed for LGE presence after adjustment for age and sex (p = 0.005), indicating that the association between mVd V1–V6 and LGE differed between patients with QRS <120 ms and those with QRS ≥120 ms.

We therefore further evaluated the correlations between CMR parameters and UHF-ECG results within the narrow QRS subgroup, demonstrating a significant positive correlation between mVd V1-V6 and LGE % (ρ=0.559, p<0.001). In the QRS<120 ms subgroup, QRS duration did not differ between LGE– (median 101.0 ms [IQR 90.8–102.8]) and LGE+ patients (median 105.0 ms [IQR 96.8–110.0]; p = 0.139).

ROC analysis was conducted to determine the area under the curve (AUC) for LGE positivity, as predicted by mVd V1-V6 in the narrow QRS complex subgroup. The ROC analysis indicated that mVd V1-V6 showed good discriminative performance for LGE positivity in patients with a QRS<120 ms (*Figure 3*). For mVd V1-V6, a cutoff value of 39.4 ms provided the optimal balance with specificity at 66.7% and sensitivity at 95.5%, with a Youden index of 0.621.

QRS morphology–based differences in patients with wide-QRS complexes

In the wide QRS subgroup, 49.1% of patients (n=26) presented with LBBB, 43.4% (n=23) with IVCD, and 7.5% (n=4) had RBBB.

In patients with LBBB, we did not find a significant difference between LGE- and LGE+ patients in terms of mVd V1-V6 duration (*Figure 2*).

Most patients with a QRS≥120 ms and concomitant IVCD had LGE on CMR (82.6%). Within this subgroup, LGE+ patients had higher mVd V1-V6 values than those without LGE (*Figure 2*). Moreover, mVd V1-V6 showed a significant correlation with LGE% in patients with IVCD (ρ=0.473, p=0.02). QRS complex duration did not differ between LGE– (median: 129.5 ms, [IQR: 125.0-140.8 ms]) and LGE+ patients (median: 136.0 ms, [IQR: 128.0-147.0 ms]; p=0.223) in the subgroup of IVCD.

ROC analysis demonstrated the discriminative ability of mVd V1–V6 for predicting LGE positivity in patients with IVCD (*Figure 3*). A threshold of 44.1 ms for mVd V1–V6 yielded the optimal trade-off between sensitivity and specificity, with sensitivity 100 %, specificity 75 %, and a Youden's index of 0.750.

Discussion

In this prospective multicentre study, we evaluated UHF-ECG-derived local depolarization duration as a candidate digital biomarker of myocardial scar. We found that UHF-ECG

conduction times under the chest leads (Vd) are associated with the presence of LGE on CMR in patients with narrow QRS complexes or IVCD, but not in patients with LBBB (*Figure 4*).

Myocardial scar is a well-established substrate for ventricular arrhythmias[16] and is identifiable by CMR LGE[17]. LGE is an independent predictor of SCD in patients with DCM[1,3], and even a low burden of LGE is associated with an increased SCD risk[18]. Given its prognostic importance, previous studies have investigated traditional ECG-based methods to detect myocardial scarring in patients with DCM[15,19], but these approaches have limited clinical applicability. The Selvester QRS Score is a widely studied 12-lead surface ECG scoring system for myocardial scar detection, particularly in patients with coronary artery disease[20]. A modified version of the score has even been validated in DCM[15]. However, its performance in patients with LBBB is uncertain[21], and moderate inter- and intraobserver variability, along with the complexity of the 32-point scoring system, limit its usefulness in everyday clinical practice. Chayanopparat et al., in a cohort of 422 patients with DCM, found that lateral inverted T-waves, intraventricular conduction delay, low voltage, and fragmented QRS complexes were independently associated with LGE[19]. They demonstrated a moderate capacity to predict LGE, with an AUC of 0.72, and they combined clinical factors (blood pressure, history of heart failure) with LVEF alongside ECG parameters in the model.

As of today, no simple, reliable ECG-based algorithm has been established as a viable alternative to CMR for LGE detection or for selecting high-risk patients for advanced imaging. Rather than replacing CMR, an ECG-derived digital biomarker could potentially serve as an upstream triage tool to identify patients in whom advanced myocardial tissue characterization is more likely to be informative.

Traditional 12-lead surface ECG operates at a frequency range below 150 Hz; however, the presence of high-frequency QRS components up to 700 Hz is associated with myocardial

pathologies[22], such as myocardial infarction and myocardial scar[23]. Jurak et al. introduced UHF-ECG in 2017[6], which features a high sampling rate and a bandwidth of up to 1500 Hz. This allows recording of high-frequency QRS components that may reveal localized myocardial abnormalities not visible on conventional ECG. In our trial, we used Vd as a specific UHF-ECG parameter to measure local conduction times and to detect myocardial scar. Vd represents an interpretable, quantitatively derived digital UHF-ECG marker linked to ventricular conduction physiology. In patients with normal QRS duration or a QRS≥120 ms and an IVCD, we derived a Vd threshold with high sensitivity for LGE detection, supporting the potential role of UHF-ECG in identifying patients who may benefit from further CMR assessment. In addition, Vd measured by UHF-ECG was correlated with the extent of LGE; longer Vd values were associated with greater LGE burden in these patient subgroups.

Vd, however, was affected by QRS duration; specifically, Vd was higher in patients with wide QRS complexes, and the optimal diagnostic Vd threshold was prolonged in patients with QRS≥120 ms and concomitant IVCD compared with those with QRS<120 ms. QRS complex morphology also affects the diagnostic performance of Vd. Across the full cohort and among patients with QRS≥120 ms, Vd did not differ significantly between those with and without LGE. However, when the wide-QRS subgroup was stratified by QRS morphology, Vd was associated with LGE in patients with IVCD, whereas this association was not observed in patients with LBBB, suggesting that QRS morphology may influence the relationship between Vd and myocardial scar. This pattern likely reflects that IVCD often indicates localized myocardial scarring, whereas LBBB represents conduction system disease and diffuse depolarization delay that can mask local abnormalities and elevate Vd independently of scar. In the case of IVCD, most patients have a myocardial scar, but Vd measured by UHF-ECG may identify the minority without a substrate for SCD.

Although Vd is affected by QRS duration, a prolonged Vd may provide additional information beyond QRS widening in the absence of LBBB. When analyses were restricted to QRS<120 ms or to QRS≥120 ms with IVCD subgroups, we did not find a significant difference in QRS complex duration between LGE- and LGE+ patients; however, Vd was longer in patients with LGE, suggesting that Vd may capture information not reflected by QRS duration alone.

UHF-ECG can be performed in a traditional clinical setting, and the ECG recording and data analysis do not require specialized expertise. Compared with previous ECG-based LGE detection methods, which rely on complex scoring systems or models that require clinical data, UHF-ECG offers a streamlined ECG-only approach to detecting LGE. Still, due to a low signal-to-noise ratio, prolonged measurement times are necessary to achieve accurate results through signal averaging. The analysis of the results is fully automated, eliminating potential bias associated with inter- and intraobserver variability.

Conclusion

UHF-ECG-derived local depolarization duration may represent an interpretable, non-invasive digital biomarker of myocardial scar in patients with DCM. However, the utility of UHF-ECG appears to be specific to patients with narrow QRS complexes or with IVCD. If confirmed in larger external cohorts, automated UHF-ECG assessment may provide a scalable approach for identifying patients who could benefit from CMR-based myocardial tissue characterization. Further prospective studies are needed to determine whether UHF-ECG can contribute to SCD risk stratification in patients with DCM.

Limitations

The study has several limitations. Although the study included 87 patients, subgroup analyses involved relatively small numbers, which may affect the robustness of the findings. The study population was restricted to patients with DCM and HNDCM, thereby limiting the

generalizability of the results to broader patient groups. Furthermore, because the recorded signals are in the microvolt range, they are more susceptible to noise interference; therefore, UHF-ECG recording should be performed with caution to minimize interfering background noise signals. The present study assessed the association of UHF-ECG with CMR-defined myocardial scar and was not designed to evaluate ventricular arrhythmias, sudden cardiac death, or other clinical outcomes. Therefore, the prognostic value of Vd cannot be inferred from these findings.

Data availability

The data supporting the findings of this study are not publicly available due to patient privacy restrictions but are available from the corresponding author upon reasonable request, subject to applicable ethical and data protection requirements.

References:

1. Di Marco, A. *et al.* Improved Risk Stratification for Ventricular Arrhythmias and Sudden Death in Patients With Nonischemic Dilated Cardiomyopathy. *Journal of the American College of Cardiology* **77**, 2890–2905 (2021).
2. Zeppenfeld, K. *et al.* 2022 ESC Guidelines for the management of patients with ventricular arrhythmias and the prevention of sudden cardiac death. *European Heart Journal* **43**, 3997–4126 (2022).
3. Di Marco, A. *et al.* Late Gadolinium Enhancement and the Risk for Ventricular Arrhythmias or Sudden Death in Dilated Cardiomyopathy. *JACC: Heart Failure* **5**, 28–38 (2017).
4. Monti, L. *et al.* Current trends and challenges in the clinical use of cardiovascular magnetic resonance: a survey from the Italian Society of Cardiology. *European Heart Journal - Imaging Methods and Practice* **3**, qyaf046 (2025).
5. El Yaman, A. *et al.* Temporal trends and geographic accessibility to cardiac magnetic resonance readers across the United States: an analysis of Medicare Part B data. *Journal of Cardiovascular Magnetic Resonance* **27**, 101921 (2025).
6. Jurak, P. *et al.* Ventricular dyssynchrony assessment using ultra-high frequency ECG technique. *J Interv Card Electrophysiol* **49**, 245–254 (2017).
7. Jurak, P. *et al.* Novel ultra-high-frequency electrocardiogram tool for the description of the ventricular depolarization pattern before and during cardiac resynchronization. *Cardiovasc electrophysiol* **31**, 300–307 (2020).
8. Leinveber, P. *et al.* UHF-ECG Outperforms QRS Duration and Morphology in Predicting Responders to Biventricular Cardiac Resynchronization Therapy. *JACC: Clinical Electrophysiology* S2405500X26004755 (2026) doi:10.1016/j.jacep.2026.04.035.

9. Curila, K. *et al.* LVSP and LBBP Result in Similar or Improved LV Synchrony and Hemodynamics Compared to BVP. *JACC: Clinical Electrophysiology* **10**, 1722–1732 (2024).
10. Curila, K. *et al.* Both selective and nonselective His bundle, but not myocardial, pacing preserve ventricular electrical synchrony assessed by ultra-high-frequency ECG. *Heart Rhythm* **17**, 607–614 (2020).
11. Pinto, Y. M. *et al.* Proposal for a revised definition of dilated cardiomyopathy, hypokinetic non-dilated cardiomyopathy, and its implications for clinical practice: a position statement of the ESC working group on myocardial and pericardial diseases. *Eur Heart J* **37**, 1850–1858 (2016).
12. Arbelo, E. *et al.* 2023 ESC Guidelines for the management of cardiomyopathies. *European Heart Journal* **44**, 3503–3626 (2023).
13. Maceira, A., Prasad, S., Khan, M. & Pennell, D. Normalized Left Ventricular Systolic and Diastolic Function by Steady State Free Precession Cardiovascular Magnetic Resonance. *Journal of Cardiovascular Magnetic Resonance* **8**, 417–426 (2006).
14. Strauss, D. G., Selvester, R. H. & Wagner, G. S. Defining Left Bundle Branch Block in the Era of Cardiac Resynchronization Therapy. *The American Journal of Cardiology* **107**, 927–934 (2011).
15. Strauss, D. G. *et al.* ECG Quantification of Myocardial Scar in Cardiomyopathy Patients With or Without Conduction Defects: Correlation With Cardiac Magnetic Resonance and Arrhythmogenesis. *Circ: Arrhythmia and Electrophysiology* **1**, 327–336 (2008).
16. Horowitz, L. N., Josephson, M. E. & Harken, A. H. Epicardial and endocardial activation during sustained ventricular tachycardia in man. *Circulation* **61**, 1227–1238 (1980).

17. Iles, L. M. *et al.* Histological validation of cardiac magnetic resonance analysis of regional and diffuse interstitial myocardial fibrosis. *European Heart Journal - Cardiovascular Imaging* **16**, 14–22 (2015).
18. Halliday, B. P. *et al.* Outcome in Dilated Cardiomyopathy Related to the Extent, Location, and Pattern of Late Gadolinium Enhancement. *JACC: Cardiovascular Imaging* **12**, 1645–1655 (2019).
19. Chayanopparat, P., Boonyasirinant, T., Prapan, N., Phoopattana, S. & Kaolawanich, Y. Electrocardiographic characteristics associated with late gadolinium enhancement and prognostic value in patients with dilated cardiomyopathy. *Front. Cardiovasc. Med.* **10**, 1281563 (2023).
20. Wagner, G. S. *et al.* Evaluation of a QRS scoring system for estimating myocardial infarct size. I. Specificity and observer agreement. *Circulation* **65**, 342–347 (1982).
21. Chaudhry, U. *et al.* Evaluation of the ECG based Selvester scoring method to estimate myocardial scar burden and predict clinical outcome in patients with left bundle branch block, with comparison to late gadolinium enhancement CMR imaging. *Noninvasive Electrocardiol* **22**, e12440 (2017).
22. Nguyên, U. C. *et al.* Ultra-High-Frequency ECG in Cardiac Pacing and Cardiac Resynchronization Therapy: From Technical Concept to Clinical Application. *JCDD* **11**, 76 (2024).
23. Langner, P. H., Geselowitz, D. B. & Mansure, F. T. High-frequency components in the electrocardiograms of normal subjects and of patients with coronary heart disease. *American Heart Journal* **62**, 746–751 (1961).

AUTHOR CONTRIBUTIONS STATEMENT

R. Papp collected data, performed the statistical analyses, and drafted the manuscript. N.L. contributed to data collection. L.M. and Z.T. collected data and reviewed the manuscript. M.R. contributed to the statistical analyses and critically reviewed the manuscript. H.V. and B.M. acquired funding and provided resources. P.L. and K.C. provided resources, collected data, and critically reviewed the manuscript. R. Panovsky and L.S. critically reviewed the manuscript. C.C. collected data, provided methodological guidance, and critically reviewed the manuscript.

Figures:

Figure 1.

Title: Local Depolarization Duration (Vd) Determined by Ultra-High-Frequency ECG (UHF-ECG)

Caption: UHF-ECG requires conventional ECG lead positions with two additional leads (A). Vd was defined as the time interval at the half-maximum amplitude of the ultra-high-frequency QRS complex in precordial leads (B). The width of the depolarization map in each lead (V1-V8) represents the local depolarization duration (C). Corresponding values in milliseconds are displayed in the green box next to each map. The mean Vd from leads V1-V6 was utilized in our analysis.

Images A and B are adapted from Jurak P et. al. Cardiovasc electrophysiol. 2020;31:300–307.

Figure 2.

Title: Comparison of Local Depolarization Duration and the Presence of Late Gadolinium Enhancement Across QRS Subgroups

Caption: Mean local depolarization duration in precordial leads V1-V6 (mVd V1-V6) was compared in the subgroup of patients with narrow (A) and wide (B) QRS complexes, stratified by the presence of late gadolinium enhancement (LGE). A significant difference was found in the narrow QRS complex group (A), whereas no difference was detected in the wide QRS complex group (B). In the wide QRS subgroup with left bundle branch block (C), mVd V1-V6 did not differ by the presence of LGE, whereas in patients with intraventricular conduction delay, mVd V1-V6 was significantly higher in LGE-positive cases (D)

Figure 3.

Title: Performance of Local Depolarization Duration in Detecting Late Gadolinium Enhancement

Caption: Receiver operating characteristic curve assessing the mean local depolarization duration of leads V1-6 in predicting late gadolinium enhancement positivity in patients with QRS<120 ms (A) and in patients with QRS≥120 ms and intraventricular conduction delay (B)

Figure 4.

Title: The Role of Ultra-High-Frequency ECG in Myocardial Scar Assessment in Dilated Cardiomyopathy

Caption: Among patients with dilated cardiomyopathy, higher mVd V1–V6 measured by ultra-high-frequency electrocardiography was associated with a greater extent of late gadolinium enhancement in the narrow QRS (<120 ms) and intraventricular conduction delay subgroups, supporting the potential utility of ultra-high-frequency electrocardiography for noninvasive myocardial scar assessment.

Table 1. Baseline Characteristics

	Total population (n=87)	**QRS≥120 ms (n=53)**	**QRS<120 ms (n=34)**	**p**
Age. years	56.0 (48.0-68.0)	**63.0 (49.5-70.8)**	**52.5 (41.8-62.0)**	**0.002**
Male	67 (77.0)	40 (75.5)	27 (79.4)	0.670
Heart Failure	80 (92.0)	**52 (98.1)**	**28 (82.4)**	**0.008**
ACEi/ARB	40 (46.0)	26 (49.1)	14 (41.2)	0.472
MRA	75 (86.2)	**49 (92.5)**	**26 (76.5)**	**0.035**
BB	78 (89.7)	50 (94.3)	33 (97.1)	0.141
ARNI	38 (43.7)	25 (47.2)	13 (38.2)	0.412
SGLT2i	54 (62.1)	32 (60.4)	22 (64.7)	0.685
VT/VF	5 (5.7)	3 (5.7)	2 (5.9)	1.000
Atrial fibrillation	18 (20.7)	12 (22.6)	6 (17.6)	0.575
Hypertension	46 (52.9)	32 (60.4)	14 (41.2)	0.080
Diabetes mellitus	28 (32.2)	**23 (43.4)**	**5 (14.7)**	**0.005**
CKD	24 (27.6)	19 (35.8)	5 (14.7)	0.054
LGE+	55 (63.2)	33 (62.3)	22 (64.7)	0.818

Values are n (%) or median (interquartile range)

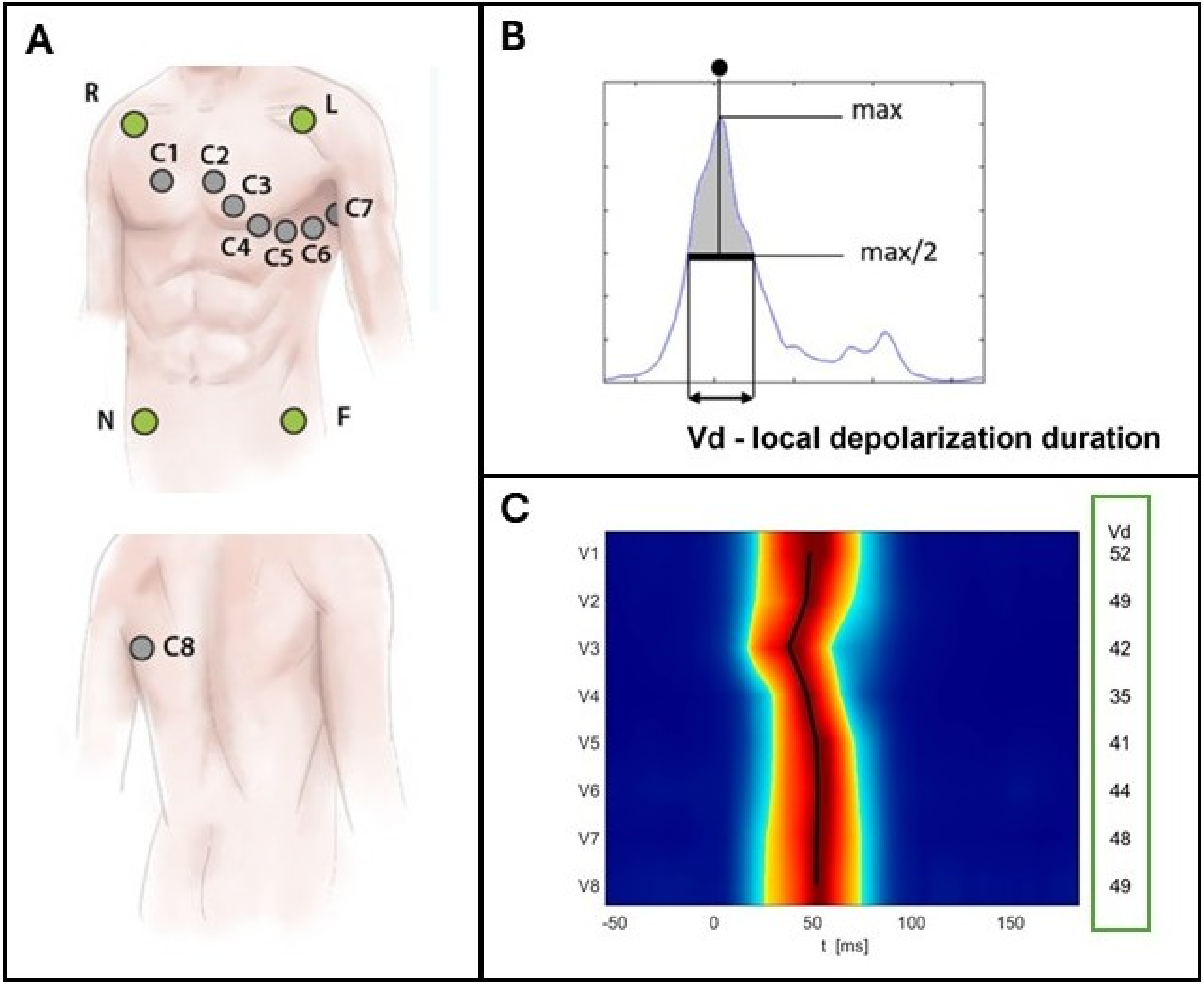
ACEi/ARB: ACE inhibitor/angiotensin receptor blocker; MRA: mineralocorticoid receptor antagonist; BB: beta blocker; ARNI: angiotensin receptor/neprilysin inhibitor, SGLT2i: SGLT2 inhibitor; VT/VF: ventricular tachycardia/ventricular fibrillation, CKD: chronic kidney disease, GFR<60 ml/min/1.73 m^2; LGE+: patients with the presence of late gadolinium enhancement

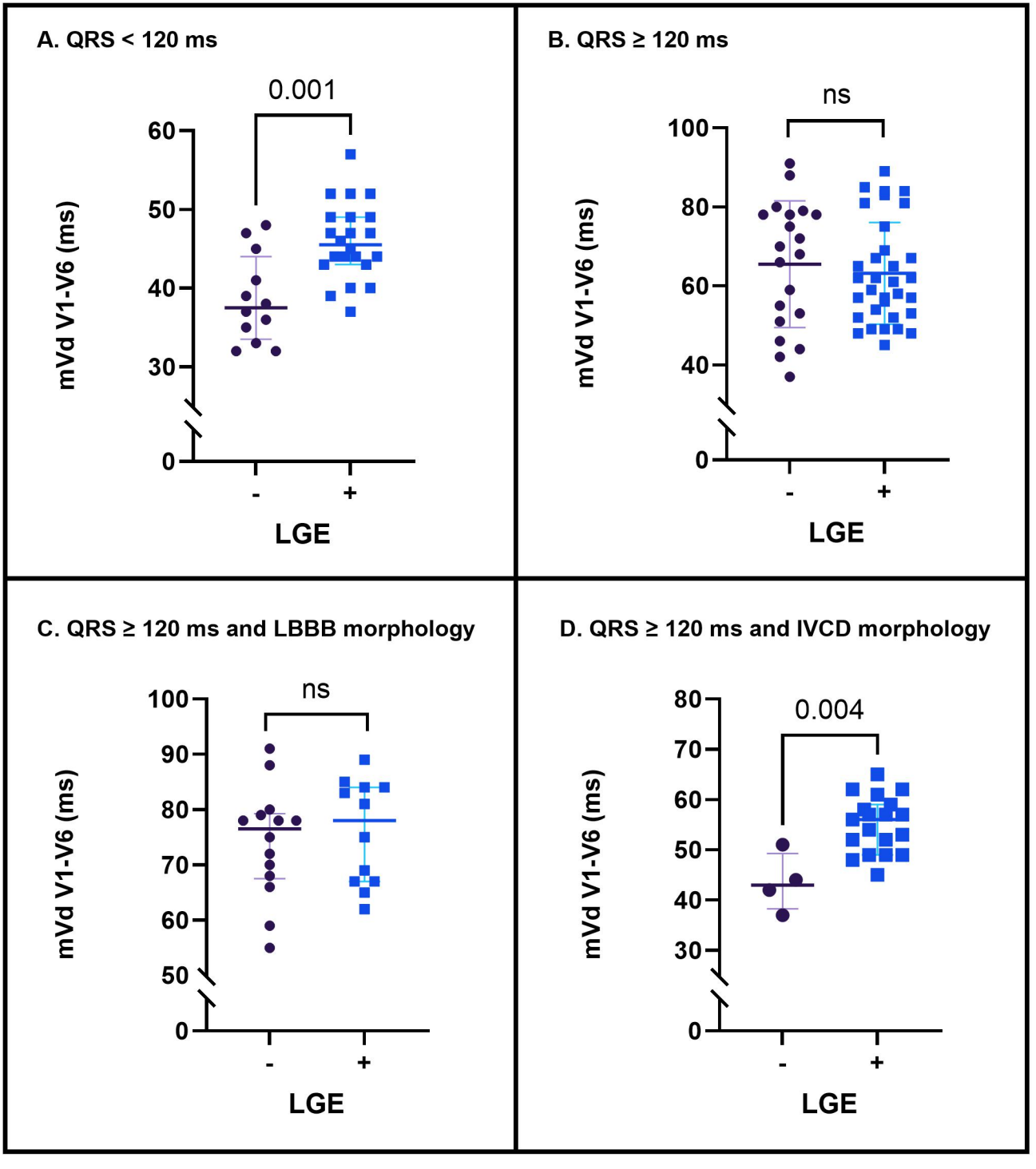
Table 2. CMR characteristics

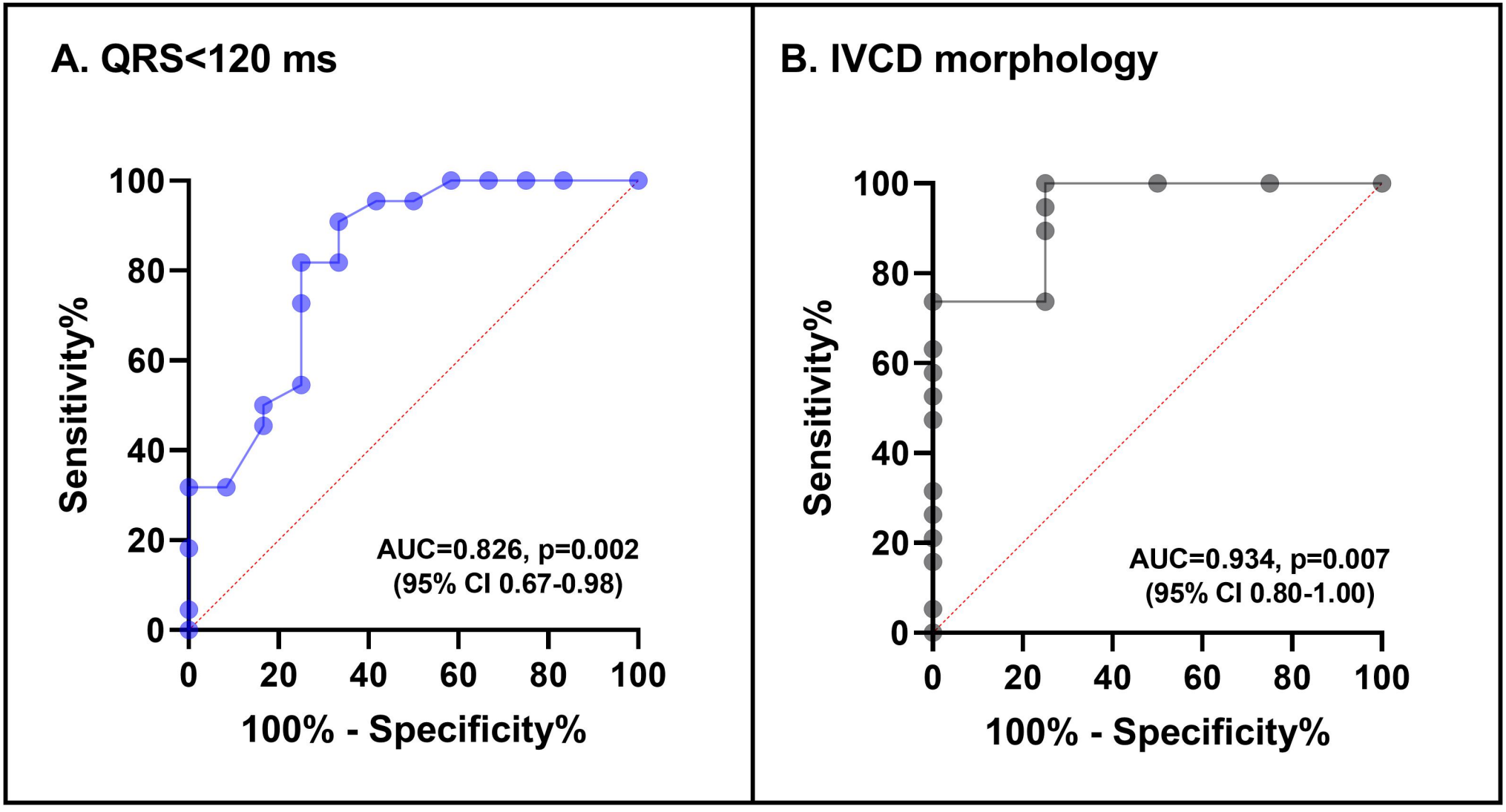
	Total population (n=87)	**QRS≥120 ms (n=53)**	**QRS<120 ms (n=34)**	**p**
LVEF (%)	30.4 (22.9-38.7)	**27.3 (21.1-34.8)**	**36.6 (26.8-42.9)**	**0.005**
LGE (%)	5.5 (0.0-11.3)	4.0 (0.0-11.0)	6.3 (0.0-13.8)	0.568
LVEDVi (ml/m2)	126.0 (107.0-163.0)	127.0 (112.5-166.3)	116.0 (100.4-155.3)	0.232
LVESVi (ml/m2)	85.0 (67.0-116.5)	89.0 (74.5-122.7)	78.0 (53.5-113.9)	0.099
LVMi (g/m2)	69.0 (60.0-88.4)	70.3 (60.5-94.8)	68.0 (58.7-80.0)	0.204

Values are median (interquartile range)

LVEF: left ventricular ejection fraction; LGE: late gadolinium enhancement; LVEDVi: left ventricular end-diastolic volume indexed to body surface area; LVESVi: left ventricular end-systolic volume indexed to body surface area; LVMi: left ventricular mass index


A
R
L
C1
C2
C3
C4
C5
C6
C7
N
F
C8
B
max
max/2
Vd - local depolarization duration
C
V1
V2
V3
V4
V5
V6
V7
V8
-50
0
50
100
150
t [ms]
Vd
52
49
42
35
41
44
48
49


A. QRS < 120 ms
0.001
mVd V1-V6 (ms)
60
50
40
30
0
-
+
LGE
B. QRS ≥ 120 ms
ns
mVd V1-V6 (ms)
100
80
60
40
0
-
+
LGE
C. QRS ≥ 120 ms and LBBB morphology
ns
mVd V1-V6 (ms)
100
90
80
70
60
50
0
-
+
LGE
D. QRS ≥ 120 ms and IVCD morphology
0.004
mVd V1-V6 (ms)
80
70
60
50
40
30
0
-
+
LGE


A. QRS<120 ms
Sensitivity%
100
80
60
40
20
0
0
20
40
60
80
100
100% - Specificity%
AUC=0.826, p=0.002
(95% CI 0.67-0.98)
B. IVCD morphology
Sensitivity%
100
80
60
40
20
0
0
20
40
60
80
100
100% - Specificity%
AUC=0.934, p=0.007
(95% CI 0.80-1.00)

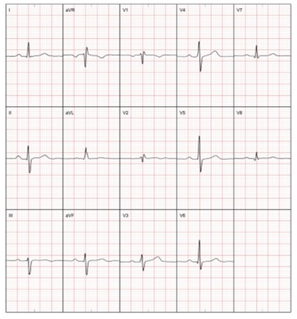
The Role of Ultra-High-Frequency ECG in Myocardial Scar Assessment in Dilated Cardiomyopathy

DCM and QRS<120 ms or IVCD

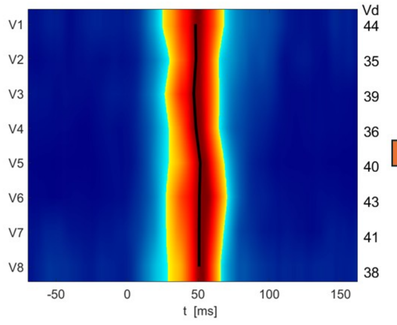
UHF-ECG recording

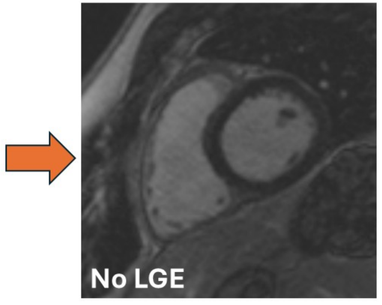
CMR

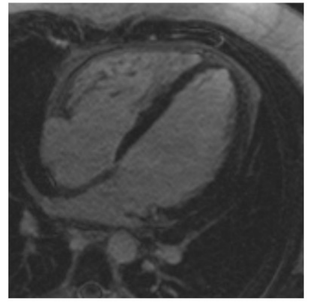
QRS = 102 ms



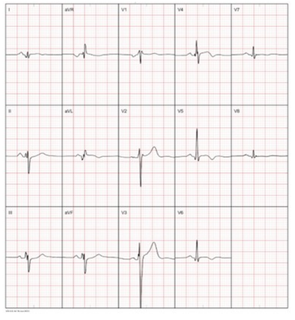
mVd V1-V6 = 39 ms







QRS = 99 ms



mVd V1-V6 = 47 ms

