

Fragmented QRS: Electrophysiological Bases, Pathophysiological Mechanisms, and Clinical Prognostic Significance

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Cite as: Köroğlu S, Aksu E, Gemci E. Fragmented QRS: Electrophysiological Bases, Pathophysiological Mechanisms, and Clinical Prognostic Significance. J Cukurova Anesth Surg. 2026;9(3):1074-1086. doi: 10.36516/jocass.1997597

Received: 17.06.2026, Accepted: 22.09.2026, Published: 30.09.2026, CC BY-NC 4.0

Abstract

Background: Fragmented QRS (fQRS) is characterized by morphological irregularities in ventricular depolarization on a standard 12-lead surface electrocardiogram (ECG) and is considered a non-invasive indicator of myocardial conduction heterogeneity. Microstructural changes such as non-uniform anisotropy, gap junction reorganization, and interstitial fibrosis can disrupt the propagation of the electrical impulse, leading to notching in the QRS complex. **Methods:** This study is designed as a narrative review to evaluate the electrophysiological basis and clinical implications of fQRS. A literature search was conducted in the PubMed, Scopus, and Web of Science databases to include peer-reviewed articles published between 2006 and 2025 that addressed fQRS, myocardial scarring, and ventricular arrhythmias (VA). **Results:** Current data indicate that the presence of a fQRS shows a strong correlation with myocardial scarring, particularly in ischemic cardiomyopathies, and may serve as an independent risk marker for VA and cardiac mortality. Additionally, it has been reported that in heart failure (HF) and certain channelopathies, fQRS carries prognostic value as a superficial reflection of electrical remodeling. However, the fact that evaluation methods are largely visual and qualitative, along with interobserver variability and dependence on ECG filter settings, limits the clinical utility of this finding. **Conclusion:** Fragmented QRS has the potential to provide important prognostic information as an electrocardiographic indicator of myocardial fibrosis and conduction heterogeneity. However, standardized definition criteria, quantitative analysis methods, and large-scale prospective studies are required for its integration into routine clinical practice.

Keywords: Arrhythmias, electrical remodeling, electrocardiography, fragmented QRS.

1. Introduction

The temporal and spatial homogeneity of electrical activation in the ventricular myocardium is a fundamental physiological requirement for the effective maintenance of cardiac mechanical synchronization and pump function. In the traditional electrocardiographic approach, ventricular conduction abnormalities are largely defined and classified based on the duration of the QRS complex. However, microstructural remodeling processes occurring in myocardial tissue profoundly affect electrical conduction. In

particular, interstitial fibrosis, disruption of cellular architecture, and changes in gap junction organization lead to significant irregularities in conduction properties¹. These changes can result in the emergence of significant electrical heterogeneity in the myocardium even when the QRS duration remains within normal limits (≤ 120 ms)^{2,3}. This suggests that electrocardiographic evaluations based solely on conduction time may be limited in reflecting the underlying electrophysiological substrate. In this context, fQRS, which reflects the morphological characteristics of electrical activation, has been defined as a potential indicator of myocardial conduction heterogeneity on the surface ECG. Although the role of fQRS in detecting subclinical myocardial damage and its clinical value in cardiovascular risk stratification are receiving increasing attention in the current literature, the certainty of this relationship has not yet been fully established.

2. Methods

This study was designed as a narrative review aimed at comprehensively evaluating the electrophysiological basis and clinical implications of fQRS. The literature search was conducted in the PubMed, Scopus, and Web of Science databases, limited to studies published between January 2006—the date when the diagnostic criteria for fQRS were standardized by Das et al.²—and December 2025.

The literature search was conducted by querying the keywords “fragmented QRS,” “myocardial scar,” “ventricular arrhythmias,” “cardiac resynchronization therapy,” and “electrocardiography” in various combinations using logical operators. Inclusion criteria were defined as full-text original research studies, meta-analyses, and guideline reports published in peer-reviewed journals in English or Turkish. Case reports, letters to the editor, small-sample pilot studies, and unpublished data were excluded from the scope of the study.

The selection of studies was conducted within a qualitative framework based on the evaluation of publications that were highly relevant to the topic and deemed to have sufficient methodological quality. However, due to the nature of the narrative review design, a standard quality scoring system (such as the Newcastle-Ottawa or Cochrane risk-of-bias tools) was not applied, as is typically done in systematic reviews. This constitutes a potential limitation regarding selection bias and interpretive bias.

In addition, the heterogeneity of patient populations across the included studies, differences in the electrocardiographic recording parameters used (particularly filter settings), and variations in the definition of fQRS complexes were considered as factors that could limit the generalizability of the findings. Ethics committee approval is not required for this study.

3. Ventricular Electrophysiological Architecture and Anisotropy

The propagation speed of the electrical impulse in the ventricular myocardium depends on the spatial organization of cardiomyocytes and the functional integrity of gap junction proteins, particularly Connexin-43, which facilitate intercellular electrical coupling. In healthy myocardium, electrical activation is characterized by uniform anisotropy, where impulses are conducted more rapidly along the long axis of the fibers and exhibit direction-dependent conduction properties. When myocardial fibrosis develops, this pattern is disrupted, resulting in non-uniform anisotropy where conduction becomes spatially irregular. In this pathological environment, the electrical impulse is forced to change direction as it passes around fibrotic barriers; as a result, conduction slows, the wavefront fragments, and local conduction delays occur. These complex electrophysiological changes manifest on the surface ECG as notches and multiple deflections within the QRS complex⁴.

4. Definition and Electrocardiographic Criteria

Fragmented QRS is defined as morphological abnormalities observed in at least two consecutive leads corresponding to a coronary artery supply area on a standard 12-lead ECG (filter range: 0.16–100 Hz)². According to the criteria defined by Das et al., fQRS morphology is classified based on QRS duration.

(a) Narrow QRS (<120 ms): Characterized by additional notches on the R or S wave, an RSR' pattern, or the presence of more than one R' wave. These findings are generally considered to be the electrocardiographic reflection of localized conduction delay and microstructural heterogeneity.

(b) Wide QRS (≥ 120 ms): Defined by the presence of more than two distinct notches on the R or S wave in the presence of bundle branch block or pacemaker rhythm. This condition is associated with widespread myocardial scarring and severe conduction disorganization.

5. Clinical Manifestations and Prognostic Significance

Fragmented QRS is considered a marker of myocardial conduction heterogeneity on the surface ECG across various cardiovascular phenotypes. However, the limited level of evidence in the current literature and the heterogeneous nature of study populations lead to variability in the clinical and prognostic value of fQRS depending on the specific disease.

5.1. Heart Failure and Fragmented QRS

5.1.1. Heart Failure with Reduced Ejection Fraction

Heart failure with reduced ejection fraction (HFrEF) is a complex pathophysiological process characterized by structural remodeling, interstitial fibrosis, ventricular dilation, and intramyocardial conduction delay. This environment of structural and electrical remodeling creates a suitable foundation for the emergence of fQRS morphology on the surface ECG. A growing body of evidence in the literature indicates that the presence of fQRS is consistently associated with adverse clinical outcomes in patients with HFrEF. A recent meta-analysis reported that all-cause mortality was increased in HFrEF patients who had a fQRS on the baseline ECG, with the risk increase reaching approximately 1.63-fold⁵. Furthermore, the association of fQRS with major ventricular arrhythmic events suggests that this finding reflects not only the structural burden of the disease but also electrical instability and an arrhythmogenic substrate. Systematic reviews and meta-analyses examining HF patients evaluated for primary prevention have demonstrated that fQRS is associated with VA and all-cause mortality; these studies particularly emphasize that a fQRS may serve as a risk marker in HFrEF population who are candidates for an implantable cardioverter defibrillator (ICD)⁶. In this context, a fQRS can be considered a complementary parameter that may provide additional prognostic value in patients with HFrEF, in addition to traditional risk markers such as EF and QRS duration.

5.1.2. Heart Failure with Preserved Ejection Fraction

Heart failure with preserved EF (HFpEF) is a more heterogeneous syndrome compared to HFrEF and is associated with diastolic dysfunction, microvascular dysfunction, diffuse interstitial fibrosis, and increased ventricular stiffness^{7,8}. Therefore, while the clinical significance of fQRS in HFpEF may initially appear less clear, current data suggest that this finding is not merely an incidental electrocardiographic variant. The presence of a fQRS in patients with HFpEF has been associated with more pronounced myocardial damage and more advanced impaired mechanical function. In a large cohort of patients with HFpEF, the presence of a fQRS—particularly when detected in the anterior and lateral leads—was found to be associated with higher BNP and troponin levels, more

myocardial perfusion defects, worse diastolic indices, and slower coronary flow^{1,2}. Although data on fQRS in the population with HFpEF are limited from a prognostic perspective, a large-scale cohort study has demonstrated that the presence of a fQRS is associated with elevated natriuretic peptide and troponin levels, impaired myocardial deformation parameters, signs of microvascular dysfunction, and poor clinical outcomes⁹. However, while the clinical utility of fQRS in HFpEF is promising, the current level of evidence is insufficient to support its integration into routine risk classification algorithms. Nevertheless, from a practical standpoint, in settings where advanced imaging methods are not readily available, fQRS may be considered a warning sign suggesting more severe myocardial involvement in patients with HFpEF.

5.1.3. Cardiac Resynchronization Therapy Response and Electrical Synchronization

Although cardiac resynchronization therapy (CRT) provides clinical and structural improvement in selected HF patients with a wide QRS complex, an adequate response is not achieved in approximately 30–40% of cases. This situation has highlighted the need for additional markers that can more accurately predict treatment response. Fragmented QRS is a parameter of interest in this context because it reflects ventricular conduction heterogeneity and widespread myocardial scarring/fibrosis^{10–13}. In particular, data from systematic reviews and meta-analyses indicate that fQRS is associated with intraventricular dyssynchrony and can independently predict non-response to CRT¹³.

Findings regarding the timing of fragmentation within the QRS complex are also clinically significant. A short duration from the onset of the QRS complex to the point where fragmentation appears has been associated with a lack of response to CRT, particularly in non-ischemic HF¹¹. Conversely, the regression or disappearance of fQRS following CRT may parallel reverse remodeling and clinical improvement, suggesting that fQRS could serve as a dynamic marker of treatment response¹².

Indeed, current guidelines primarily rely on QRS duration, left bundle branch block pattern, and EF when determining indications for CRT; fQRS has not yet been incorporated into routine decision algorithms¹⁴. Although fQRS is a promising complementary biomarker for patient selection in CRT, it requires standardization and prospective validation for clinical use; therefore, evaluating it within a multimodal risk stratification framework may be the most appropriate approach.

5.1.4. Relationship with Indications for Implantable Cardioverter Defibrillator

Although the indication for implanting an ICD for primary prevention is largely based on left ventricular EF, a low left ventricular EF alone cannot distinguish the risk of SCD with sufficient accuracy. This highlights the need for additional electrical markers that more directly reflect the arrhythmogenic substrate. Fragmented QRS, as a reflection of myocardial scarring and conduction heterogeneity on the surface ECG, is a prominent non-invasive parameter in this context^{6,15,16}.

In patients with HF who have received an ICD for primary prophylaxis, the presence of a fQRS complex—particularly when observed in multiple leads—has been independently associated with appropriate ICD shocks and ventricular arrhythmic events. In this regard, fQRS can be considered a complementary risk indicator reflecting not only the extent of structural myocardial damage but also the degree of electrical instability^{6,15}.

A recent systematic review and meta-analysis supports the association between fQRS and the development of VA in HF patients with an indication for an ICD⁶. Similarly, in large patient cohorts, the presence of a fQRS has been found to be independently associated with long-term adverse clinical outcomes and arrhythmic events¹⁶. However, current evidence indicates that a fQRS alone is not sufficient to guide the decision for an ICD. Indeed, in multivariate analyses, the predictive value of a fQRS often becomes meaningful

when evaluated in conjunction with established parameters such as left ventricular EF, QRS duration/morphology, and myocardial scar burden^{6,16}.

Therefore, the most clinically rational approach is to incorporate fQRS into a multi-modal, multi-parameter risk stratification model that includes left ventricular EF, underlying etiology, scar burden determined by cardiac magnetic resonance imaging (CMR), and biomarkers. This approach can reduce unnecessary ICD implantations by enabling more accurate patient selection, particularly in patients with borderline left ventricular EF values, while also contributing to the more effective identification of high-risk individuals.

5.2. Coronary Artery Disease and Fragmented QRS

5.2.1. Fragmented QRS in Acute Coronary Syndrome

Acute coronary syndrome represents a dynamic spectrum of myocardial ischemia and necrosis, and the electrical conduction abnormalities that develop during this process may be reflected on the surface ECG. Fragmented QRS is a frequently observed finding, particularly in patients with ST-segment elevation and non-ST-segment elevation myocardial infarction, and is considered an electrophysiological reflection of local conduction delay and heterogeneous depolarization associated with acute ischemia^{2,17}. In this regard, fQRS is not merely a morphological variant but also serves as a non-invasive and accessible indicator of underlying myocardial damage.

The timing of the appearance of fQRS during acute coronary syndrome is clinically significant. Fragmented QRS developing in the early phase may reflect transient conduction delay due to acute ischemia; whereas persistent or late-onset fQRS is more closely associated with irreversible myocardial damage, necrosis, and scar formation¹⁸. The regression or disappearance of fQRS after reperfusion is interpreted in favor of limited myocardial damage and successful reperfusion; whereas the presence of persistent or newly developing fQRS has been associated with a larger infarct area and persistent conduction abnormalities^{18,19}.

When evaluated in terms of reperfusion success, the presence of a fQRS complex may serve as an indirect indicator of suboptimal reperfusion, particularly in patients with ST-segment elevation myocardial infarction who undergo primary percutaneous coronary intervention. Indeed, studies have shown that patients with fQRS exhibit lower TIMI (thrombolysis in myocardial infarction) flow grades and inadequate ST-segment resolution¹⁸. These findings suggest that fQRS may reflect not only epicardial vessel patency but also the quality of perfusion at the microvascular level.

In this context, the relationship between microvascular obstruction, the “no-reflow” phenomenon, and a fQRS is noteworthy. No-reflow is characterized by inadequate perfusion at the microcirculatory level despite epicardial vessel patency and is closely associated with a poor prognosis. In CMR studies, the presence of a fQRS has been shown to correlate with late gadolinium enhancement (LGE) and areas of microvascular obstruction; thus, it reflects a broader, more heterogeneous, and deeper myocardial injury²⁰. These observations support the notion that a fQRS may be an electrocardiographic reflection of microstructural damage beyond macroscopic necrosis.

5.2.2. Fragmented QRS in Chronic Coronary Syndrome

Chronic coronary syndrome is characterized by persistent myocardial damage resulting from recurrent episodes of ischemia and/or a previous myocardial infarction. The fibrosis and scar tissue formed during this process lead to heterogeneity in intramyocardial conduction, paving the way for the emergence of a fQRS morphology on the surface ECG^{2,17}. Therefore, fQRS is considered not only an electrical variant in patients with chronic coronary syndrome but also a non-invasive and accessible indicator of underlying structural myocardial damage.

The role of fQRS in detecting silent ischemia and subclinical myocardial damage is particularly noteworthy. It has been demonstrated that the presence of fQRS is associated with prior myocardial infarction and myocardial scarring even in patients without clinically pathological Q waves². This finding may indicate that fQRS has the potential to reflect subclinical ischemia and scarring with higher sensitivity compared to classical electrocardiographic markers.

In patients with a history of myocardial infarction, fQRS stands out as an important marker of scar presence. In studies using CMR, it has been reported that the leads showing a fQRS exhibit a significant correlation with segmental myocardial scar areas detected by delayed gadolinium enhancement²⁰. This finding demonstrates that a fQRS can provide anatomical information not only through its presence but also through its localization.

5.3. *Fragmented QRS in Cardiomyopathies*

5.3.1. *Dilated Cardiomyopathy and Fragmented QRS*

Dilated cardiomyopathy (DCM) is characterized by ventricular dilatation and systolic dysfunction, reflecting a complex myocardial remodeling process accompanied by diffuse interstitial and replacement fibrosis. These structural changes cause heterogeneity in intramyocardial conduction, paving the way for the emergence of a fQRS morphology on the surface ECG. In this context, fQRS is considered not merely a conduction abnormality in DCM, but a non-invasive indicator of the underlying fibrotic substrate and electrical irregularity².

Cardiac magnetic resonance studies have demonstrated that the presence of fQRS is closely associated with the burden of myocardial fibrosis. It has been reported that in patients with fQRS, fibrotic areas defined by LGE are more widespread and show partial correlation with the distribution of electrocardiographic fragmentation²¹. These findings suggest that fQRS may serve as a practical marker indirectly reflecting the fibrosis burden in situations where access to advanced imaging methods is limited. Although fQRS serves as a comprehensive indicator of structural and electrical remodeling in DCM, stronger prospective evidence is needed to standardize its clinical use.

5.3.2. *Hypertrophic Cardiomyopathy and Fragmented QRS*

Hypertrophic cardiomyopathy (HCM) is a genetic disorder characterized by myocardial hypertrophy, myocyte disarray, and interstitial fibrosis. These structural abnormalities lead to heterogeneity in intramyocardial conduction, creating the conditions for the appearance of a fQRS morphology on the surface ECG. In this context, fQRS is considered not merely a conduction anomaly in HCM, but rather an electrophysiological reflection of the underlying myocardial organizational disorder and fibrotic substrate^{17,22}.

Cardiac magnetic resonance data indicate that the presence of fQRS is closely associated with myocardial fibrosis. A significant correlation has been reported between the presence and extent of fibrotic areas defined by and fQRS; in particular, it has been shown that fQRS observed in the septal and anterolateral segments may correlate with the fibrotic burden in these regions²³. These findings suggest that fQRS may serve as an accessible marker that indirectly reflects the fibrosis burden in HCM.

Clinically, the most important potential role of fQRS is its association with arrhythmic risk. The presence of fQRS in patients with HCM has been evaluated as an indicator of arrhythmogenic substrate; some studies have reported that non-sustained ventricular tachycardia (VT) and other arrhythmic events are observed more frequently in cases where fQRS is detected²⁴. Therefore, fQRS can be considered a complementary parameter that may contribute to risk stratification in addition to established markers such as maximum wall thickness, family history, and syncope. However, the prognostic value of fQRS in HCM has not yet been fully standardized.

5.3.3. Restrictive Cardiomyopathy and Fragmented QRS

Restrictive cardiomyopathies represent a group of myocardial diseases characterized by impaired ventricular filling, although systolic function is often preserved. This condition is frequently associated with infiltrative diseases, particularly cardiac amyloidosis, and is characterized by widespread myocardial involvement. These infiltrative processes may contribute to the emergence of a fQRS morphology on the surface ECG by causing significant heterogeneity in intramyocardial conduction²⁵.

In the context of restrictive physiology, a fQRS is considered a non-invasive indicator of diffuse myocardial involvement and conduction abnormalities. Particularly in infiltrative diseases such as amyloidosis, fQRS observed alongside low-voltage QRS complexes may represent a combined reflection of infiltrative burden and electrical heterogeneity. This suggests that fQRS may reflect not only fibrotic changes but also infiltrative myocardial processes²⁶.

Clinically, the prognostic value of fQRS in restrictive cardiomyopathies has been evaluated in a limited number of studies. While current data suggest that the presence of fQRS may be associated with a greater disease burden, increased risk of arrhythmic events, and adverse clinical outcomes, the generalizability of these findings remains limited.

5.3.4. Arrhythmogenic Right Ventricular Cardiomyopathy and Fragmented QRS

Arrhythmogenic right ventricular cardiomyopathy (ARVC) is a cardiomyopathy characterized by fibro-fatty changes in the right ventricular myocardium, progressive structural remodeling, and a marked arrhythmogenic tendency. These structural changes may lead to slowing and heterogeneity in intramyocardial conduction, thereby setting the stage for the emergence of a fQRS morphology on the surface ECG. Therefore, a fQRS is considered not merely a depolarization abnormality in ARVC, but a non-invasive reflection of the underlying structural damage and conduction irregularities.

Although the epsilon wave is among the classic depolarization findings in ARVC, its diagnostic sensitivity is limited. In contrast, QRS fragmentation, particularly when detected in the right precordial leads, is a diagnostically significant finding in ARVC and is frequently reported in some series. Peters et al. reported that QRS fragmentation on a standard 12-lead ECG carries high diagnostic value for ARVC²⁷. However, rather than stating that a fQRS is “definitely more sensitive” than the epsilon wave, it is more appropriate to suggest that it can be interpreted as an indicator of an early or additional depolarization abnormality.

From an electrophysiological perspective, a fQRS is associated with the ventricular arrhythmia substrate in ARVC. In a study published by Canpolat et al., it was reported that a fQRS predicts fatal and nonfatal arrhythmic events in patients with ARVC²⁸. Similarly, in another study, QRS fragmentation was shown to be associated with arrhythmic outcomes such as SCD, recurrent VT, primary ventricular fibrillation, and repeated ICD discharges²⁹. These data suggest that fQRS may reflect not only structural disease but also arrhythmogenic fragility in ARVC.

Supportive data also exist regarding the localization value of fQRS. Tschabrunn et al. demonstrated a relationship between QRS fragmentation patterns on a 12-lead ECG and regions of endocardial and epicardial abnormal electro-anatomical substrates in ARVC³⁰. This finding suggests that fragmentation detected on the surface ECG may provide indirect topographic information regarding underlying abnormal voltage fields and pathological conduction regions, at least in some cases.

Consequently, a fQRS complex can be considered a practical indicator of fibro-fatty myocardial transformation, conduction heterogeneity, and arrhythmogenic substrate on the surface ECG in ARVC. However, standardized definition criteria and broader,

prospective validation studies are still needed for its integration into clinical decision-making processes.

5.4. *Arrhythmic Diseases and Electrical Instability*

5.4.1. *Supraventricular Arrhythmias and Fragmented QRS*

Supraventricular arrhythmias, particularly atrial fibrillation (AF), are closely associated with atrial structural remodeling and fibrosis. Atrial fibrosis facilitates the development of re-entry mechanisms by causing conduction slowing, anisotropy, and electrical heterogeneity. Although a fQRS is a finding reflecting ventricular depolarization, its presence is thought to represent the widespread myocardial fibrotic burden and electrical irregularity that frequently accompany it, and thus may parallel structural changes at the atrial level³¹.

In this context, a significant association between fQRS and the development of AF is supported by an increasing number of studies. In particular, a recent study conducted in a population with acute myocardial infarction demonstrated that the presence of a fQRS, when evaluated in conjunction with clinical risk scores, is an independent and significant predictor of the development of new-onset AF³².

Fragmented QRS also draws attention in terms of predicting AF recurrence. It has been reported that the presence of fQRS detected prior to catheter ablation is associated with post-procedural AF recurrence rates; this finding may reflect a more severely impaired atrial substrate³³. These findings support the notion that fQRS is not merely an electrocardiographic phenomenon reflecting ventricular conduction abnormalities; it may also serve as a broader indicator of myocardial fibrosis, electrical heterogeneity, and remodeling processes. Indeed, it is thought that this structural-electrical heterogeneity demonstrated at the ventricular level is similarly associated with fibrotic remodeling in the atrial myocardium and may contribute to the development of AF. However, a significant portion of the current data is based on observational studies, and larger, prospective studies are needed to validate the independent predictive value of fQRS in different clinical scenarios.

5.4.2. *Ventricular Arrhythmias and Fragmented QRS*

Ventricular arrhythmias, particularly monomorphic VT, are predominantly associated with scar-related re-entry mechanisms that develop against a background of structural heart disease. In this context, fQRS stands out as a reflection of myocardial scarring, conduction delay, and electrical heterogeneity on the surface ECG.

When evaluated in the context of monomorphic VT, the presence of fQRS is frequently associated with the presence of scar-related re-entry circuits. In a study conducted in patients with non-ischemic cardiomyopathy, the presence of fQRS was shown to be significantly associated with both all-cause mortality and ventricular arrhythmic events³⁴. Similarly, in patients with non-ischemic cardiomyopathy undergoing CRT, the presence of fQRS has been reported to be an independent risk factor for ventricular arrhythmic events³⁵. These findings support the notion that a fQRS is not merely an indicator of structural damage but also a clinical reflection of arrhythmogenic potential.

Electro-anatomical mapping studies provide a more detailed explanation of the relationship between fQRS and arrhythmogenic substrate. It has been reported that low-voltage areas, late potentials, and fractionated ECGs identified during catheter ablation frequently overlap with myocardial segments corresponding to the leads where fQRS is observed. This overlap suggests that fQRS may provide indirect information regarding scar localization via the surface ECG and may contribute to the identification of potential ablation targets.

In this context, the fQRS can be considered not only a risk marker in VA but also a parameter that may contribute to the non-invasive assessment of the arrhythmogenic

substrate. However, a significant portion of current studies are based on limited sample sizes and heterogeneous patient populations, and stronger evidence is needed, particularly regarding localization accuracy and integration into treatment strategies.

In conclusion, fQRS can be considered an electrocardiographic reflection of scar-related re-entry circuits in the context of VA and is particularly associated with the development of monomorphic VT. However, there remains a need for large-scale, prospective, and standardized studies to facilitate its integration into clinical decision-making algorithms.

5.4.3. Sudden Cardiac Death and Fragmented QRS

Sudden cardiac death is a significant cardiovascular outcome that predominantly develops against a background of ventricular tachyarrhythmias, and fQRS emerges as a non-invasive marker of the arrhythmogenic substrate associated with this risk. The presence of fQRS has been shown to be significantly associated with ventricular tachyarrhythmias and arrhythmic events in both ischemic and non-ischemic cardiomyopathy populations^{34,35}. However, studies evaluating the direct relationship between fQRS and SCD are limited, and current data mostly point to an indirect relationship via ventricular arrhythmic events. Therefore, fQRS should be considered not as a direct predictor of SCD, but rather as an indicator of the arrhythmogenic substrate that predisposes to SCD.

5.4.4. Channelopathies and Fragmented QRS

Channelopathies are primary electrical disorders caused by ion channel dysfunction in the absence of structural heart disease and are associated with a risk of SCD. In conditions within this group, such as Brugada syndrome, long QT syndrome, and early repolarization syndrome, subtle conduction abnormalities and electrical heterogeneity on the surface ECG are of critical clinical importance. Although fQRS is classically associated with scarring and fibrosis in structural heart diseases, it can also manifest as the electrocardiographic reflection of microscopic conduction heterogeneity in channelopathies¹⁷.

In the context of Brugada syndrome, fQRS is particularly observed in right precordial leads and is associated with an increased risk of arrhythmias. This finding is thought to reflect local conduction delay and repolarization heterogeneity in the epicardium of the right ventricular outflow tract. Indeed, it has been reported that clinical events such as ventricular fibrillation and syncope are observed more frequently in patients with a fQRS³⁶. Therefore, a fQRS can be considered a complementary risk marker in this patient group.

While the arrhythmia mechanism in long QT syndrome is primarily based on prolonged repolarization and triggered activity, it has been suggested that the presence of a fQRS may reflect heterogeneity in the ventricular depolarization phase. It suggests that, in this syndrome—classically considered to be based on repolarization—conduction heterogeneity may also contribute to the arrhythmogenic process. Indeed, in a study conducted on patients with acquired long QT syndrome, the presence of a fQRS was shown to be significantly associated with the development of torsades de pointes³⁷. This finding supports the notion that a fQRS may reflect not only an abnormality in ventricular depolarization but also a more complex electrical substrate that contributes to arrhythmia susceptibility.

5.5. Fragmented QRS and Artificial Intelligence Applications

Rapid advancements in digital cardiology have enabled the re-evaluation of complex signals derived from surface ECGs using advanced analytical methods. In this context, fQRS is evolving from a visual and observer-dependent finding into a parameter that can be analyzed objectively and reproducibly using artificial intelligence (AI) and machine learning algorithms. In particular, deep learning approaches have the potential to detect

subtle conduction abnormalities that are difficult for the human eye to distinguish by processing the high-dimensional features of the ECG signal^{38,39}.

Algorithms developed using models such as convolutional neural networks have achieved high accuracy rates in the automatic detection and classification of fQRS. By directly extracting features from raw ECG signals, these systems can identify not only the presence of fragmentation but also its morphological subtypes, thereby reducing inter-observer variability and offering a solution to the standardization issue⁴⁰.

From the perspective of clinical decision support systems, the integration of fQRS with AI-based analyses could make risk stratification more precise. Including fQRS features derived from the ECG in multivariate models alongside EF, biomarkers, and imaging findings may improve the prediction of clinical outcomes such as SCD, ventricular arrhythmia, and progression of HF⁴¹. This approach could provide meaningful contributions to clinical decision-making processes, particularly in patients at borderline risk.

The use of big data analytics and multicenter datasets enables a better understanding of the prognostic value of fQRS. Models developed using electronic health records and large-scale ECG databases can redefine the clinical significance of fQRS in different patient populations. In this context, fQRS is positioned not as a standalone marker but as a component of integrated risk models⁴².

In conclusion, AI-driven analyses offer a new paradigm for the identification, standardization, and clinical interpretation of fQRS. However, the integration of these technologies into routine clinical practice remains contingent upon the completion of prospective studies, multicenter validation, and regulatory processes.

6. Discussion

While the current literature supports the notion that a fQRS complex is a potential marker for cardiovascular risk stratification, its integration into routine clinical practice remains limited due to significant methodological and technical constraints.

From a technical standpoint, hardware and software differences in ECG recording systems also pose a significant limitation. In particular, the use of low-pass filter settings in the 40–100 Hz range instead of 150 Hz can suppress high-frequency components, thereby reducing the amplitude of fine notches within the QRS and potentially leading to false-negative results⁴³. This situation may cause systematic differences between devices, affecting the reliability of measurements.

The role of fQRS in clinical decision-making processes has not yet been clearly established. Fragmented QRS cannot provide structural and functional information with the same accuracy as the left ventricular EF, LGE assessed by CMR, or data from electrophysiological studies. In particular, LGE assessed by CMR remains the gold standard for determining the topographic localization and transmural extent of myocardial scarring. However, the non-invasive, low-cost, and widely accessible nature of fQRS may make it a valuable screening tool in clinical practice.

7. Conclusion

Fragmented QRS is considered a complementary biomarker that gains clinical value when positioned within a multimodal risk stratification framework, rather than serving as a standalone decision-making indicator. Standardized definition criteria, technical optimization, and prospective validation studies will be decisive in integrating this parameter into clinical practice.

Author Contribution Statement: Conceptualization: Dr. Sedat Köroğlu (A), Dr. Ekrem Aksu (B) Methodology: Dr. Sedat Köroğlu, Dr. Ekrem Aksu, Dr. Ekrem Gemci (C) Writing – original draft:

Dr. Ekrem Aksu, Dr. Sedat Köroğlu, Dr. Ekrem Gemci Writing – review & editing: Dr. Ekrem Aksu, Dr. Sedat Köroğlu, Dr. Ekrem Gemci Supervision: Dr. Ekrem Aksu

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflict of Interest: The authors declare no conflict of interest.

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