P-Wave Morphological Variability Combined with Heart Rhythm Features Reveals Distinct Pre-Onset Patterns of Paroxysmal Atrial Fibrillation

Maikel Noriega, Alba Martín-Yebra, Pyotr G. Platonov, Aleksei Savelev, Javier Marta, Juan Pablo Martínez, Leif Sörnmo, Pablo Laguna

BSICoS-I3A, Zaragoza University; CIBER-BBN, Zaragoza, Spain.

Introduction: Atrial fibrillation (AF) arises from complex interactions between focal triggers and a vulnerable atrial substrate. P-wave morphological variability (PMV) has been proposed as a dynamic marker of atrial instability preceding AF. However, its predictive value is limited by the heterogeneity of AF initiation mechanisms. This study evaluates whether PMV temporal evolution differs according to pre-AF heart rhythm patterns.

Methods: A total of 176 one-hour pre-AF ECG segments from the SPAFDB database were analyzed. Signals were filtered and transformed using Principal Component Analysis to enhance P-wave quality. PMV was computed as a normalized energy measure based on the median absolute deviation of P-wave ensembles in 2-minute subsegments with 1-minute overlap. To classify trigger patterns, a k-means clustering algorithm was applied to heart rate features derived from RR intervals (mean, root-mean square of successive differences, standard deviation, and Poincaré plot geometric descriptors).

Results: Four representative clusters showed distinct PMV dynamics (see Figure 1). Clusters with irregular rhythms and high ectopic burden exhibited a progressive increase in PMV prior to AF onset, suggesting gradual substrate destabilization. In contrast, clusters with stable or slower rhythms maintained low PMV levels, indicating AF initiation driven mainly by focal triggers without prior substrate deterioration. Ectopic activity supported these findings, with higher burden observed in clusters showing increasing PMV.

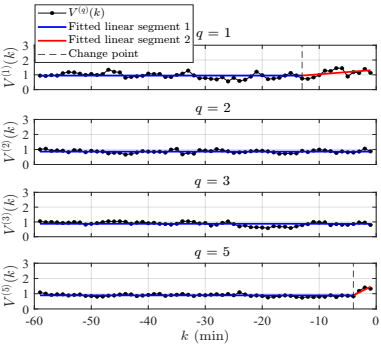

Figure 1: Cluster-specific $V^{(q)}(k)$ series with its piecewise linear fit.

Conclusion: PMV dynamics before AF are non-uniform and reflect different initiation mechanisms. Combining PMV with heart rhythm clustering enables differentiation between substrate-mediated and trigger-driven AF onset, improving pathophysiological understanding and potential prediction strategies.