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Frequency content and characteristics of ventricular conduction☆,☆☆

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Abstract The spectrum of frequencies producing the QRS complex has not been fully explored. In this manuscript we review previous studies of QRS frequency content, and discuss our novel method of the conjoint analysis of the ECG signal in six dimensions: in the domain of three space dimensions, in time domain, and in frequency domain. Orbital frequency of QRS loop is introduced as a six-dimensional characteristic of ventricular conduction, which helped to reveal inapparent ventricular conduction, and to characterize electrophysiological substrate. In this paper, we review our novel method in the historical context.

Keywords: Vectorcardiogram; Frequency content

Introduction

ECG waveform reflects depolarization and repolarization of the heart. Conduction velocity in the His–Purkinje system is the fastest, 2–4 m/s. Propagation of activation through the His–Purkinje system and ventricular myocardium forms a fast-moving QRS complex on an electrocardiogram (ECG) and by a QRS loop on a vectorcardiogram (VCG). Conduction velocity in atria is slower (0.5–1 m/s) than in the His–Purkinje system. Propagation of activation through atria forms P-wave on ECG (P-loop on VCG). Repolarization spreads very slowly and forms slow-deflecting T-wave (T-loop).

Differences in the speed of wavefront propagation through the cardiac cycle are reflected by different frequencies content of ECG waves. The content of T wave lays mostly within a range from 0 (DC) to 10 Hz. The content of P wave is characterized by 5–30 Hz frequencies. The content of QRS usually contains within 8–50 Hz frequencies while abnormal ventricular conduction is characterized by high frequencies (above 70 Hz), forming notches on the QRS. However, the full spectrum of frequencies producing the QRS complex has not been adequately explored. In this manuscript we review the history of QRS frequencies content investigations and discuss our novel method of non-invasive assessment of ventricular conduction [1].

The spectrum of frequencies producing the QRS complex of the electrocardiogram

History of electrocardiology reveals a battle between proponents and antagonists of the usefulness of measuring high frequencies within QRS complex. The importance of analyzing ECG frequency content has been recognized very early. At the beginning of the 20th-century studies attempted to determine the potential value of the various frequencies of the QRS ECG complex. Initially, Einthoven was able to perform ECG recording above 300 cycles per second using string galvanometer with a fine string less than 1 mm in length [2]. However, by the year 1912, Einthoven came to the conclusion that "the form and dimensions of the recorded E.K.G." remain the same if the movements of the string are made 10–100 times, or even infinitely faster than the certain threshold value. In 1912 Einthoven wrote [3]: "If the string reaches its new position of equilibrium within about 0.01 second or less, the instrument is rapid and at the same time sensitive enough for recording EKG with sufficient accuracy". In other words, Einthoven investigated QRS morphology recorded with various sampling rates and concluded that for practical purposes there is no additional value in recording of ECG signal with sampling frequency above 100 samples per second. Thus, in that early period Einthoven himself transitioned from being proponent to becoming the antagonist of high frequencies QRS content investigations.

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Interest in QRS frequency content was elevated in the 1930s [4] after the string galvanometer was replaced by the oscillograph [5]. The oscillograph was capable of capturing high-resolution analog signal and thus made it possible to analyze frequencies up to 1000 cycles per second, or 1000 Hz if translated to modern digital signal characteristics, accordingly. This newfound ability to capture high-resolution ECG signal catalyzed interest in a reassessment of the high frequencies value. Nevertheless, evidence of high-frequency content usefulness was not convincing enough, and opinion of antagonists of high frequencies QRS content investigations prevailed. In a statement by the US Bureau of Standards and a paper by Gilford in 1949 it was concluded that for practical purposes ECG recordings should have a sampling rate of no more than 200 samples per second.

Soon after, in 1950s–60s interest in the study of QRS frequency content increased yet again. In 1952, Langner [6] reported that while in healthy individuals most of the QRS frequency content is below 100 Hz ("100 cycles per second"), high-frequency notching and slurring within QRS complex were observed [6,7]. Langner [6] concluded that the study of the whole spectrum of QRS frequencies up to 330 Hz was needed to characterize features of the ventricular conduction. In agreement with Langner, Kerwin [7] demonstrated the need for the whole spectrum of QRS loop frequencies to be studied, and emphasized that the amplitudes of QRS complex are greatly affected by the recorded frequency bandpass [7]. Notably, in 1950s Kerwin was able to record ECG with a sampling rate of 6400 cycles per second, using a recording speed of 500 mm per second.

In 1960 Langner and Gezelowitz [8] introduced a band-pass filter for studying high frequencies within QRS, and showed that in contrast to healthy individuals, post-MI patients are characterized by high-frequency notching, slurring, and beading, which are produced by patchy fibrosis [9,10]. QRS power spectral density was further studied by Franke et al. [11], which recorded ECG signal with sampling rate of 3000 Hz and used relatively narrow band-passes of 30 Hz, detected high (up to 700 Hz) frequencies well above noise level and described distinct differences in the high frequency components of the "heart generator". Flowers et al. [12] studied the correlations of high-frequency QRS components (notching and slurring) on ECG with postmortem studies of the hearts and showed correlation of high-frequency QRS components with left ventricular enlargement, hypertrophy, and post-MI scar. Thus, multiple high-quality investigations in the 1950s–60s showed that high frequency (70–700 Hz) components could be present within QRS and that detection of the high-frequency components within QRS is meaningful and clinically significant. Importantly, investigators highlighted that it is not the size of the high-frequency notch that is clinically important, but rather the presence or absence of such an abnormal high-frequency feature.

Study of high frequencies within QRS requires high resolution of ECG recording with high sampling rate. In spite of proven clinical importance of high frequencies within QRS, antagonists of high frequencies analysis opposed the necessity of high-resolution ECG recordings. In 1960 Scher and Young [13] reported that the net contribution to the QRS by frequencies >80 Hz is less than 3%, by frequencies >90 Hz is less than 2%, and by frequencies >100 Hz is negligible. Scher and Young [13] confirmed Einthoven's findings [3] and concluded that high-frequency QRS signal studies are impractical and unnecessary, which lead to the industry decision to eliminate high frequencies from the routinely evaluated clinical ECG signal. Modern ECG machines record ECG signal in the bandpass from 0.05 (or 0.5) Hz to 100 (or 150) Hz as an industry standard. Thus, antagonists of the usefulness of measuring high frequencies within QRS complex prevailed. We believe that the historic decision to limit recorded frequencies of ECG signal negatively impacted further development of the electrocardiology field, and made studies of high QRS frequencies impossible for investigators outside of electrophysiological laboratories.

Nevertheless, high-resolution ECG containing the wide spectrum of QRS frequencies continued to be investigated in research studies that aimed to uncover mechanisms behind ECG changes. Mor-Avi et al. [14] acutely occluded left anterior descending coronary artery in dogs and showed a significant decrease in high-frequency (150–250 Hz) QRS content. Pettersson et al. [15] showed that in patients undergoing percutaneous transluminal coronary angioplasty (PTCA), acute coronary artery occlusion was detectable using high-frequency (150–250 Hz) QRS analysis, a much more sensitive marker than conventional ST-segment deviation.

In the 1970s, the novel field of invasive cardiac electrophysiology was born. Josephson et al. described mechanisms of sustained monomorphic ventricular tachycardia (VT) in patients with post-myocardial infarction (MI) scar [16], developed the techniques of left ventricular endocardial catheter mapping, electrical stimulation [17], and maneuvers to identify VT substrate, and performed the first successful surgical endocardial left ventricular VT ablation in a human [18]. Josephson's group showed that abnormal fragmented endocardial electrograms, associated with initiation of reentrant VT are characterized by high-frequency component above at least 30 Hz, and especially above 70 Hz [18]. Based on electrophysiology findings, the signal-averaged ECG (SAECG) method was developed, which implemented filtering of QRS with 25 (40)–250 Hz bandpass with the goal to detect and characterize abnormal activation at the end of QRS complex [19] in VT cases. The SAECG showed some value in risk stratification for sudden cardiac death [20,21]. However, SAECG was not capable of detecting abnormal conduction if it occurs early on within the QRS, as SAECG was designed to look specifically for late potentials [22].

In summary, over more than a century's worth of investigations of the QRS frequency content have shown that QRS is composed of a wide range of frequencies from the minuscule to at least 700 Hz. Characterization of QRS frequency content is meaningful. Specific features of ventricular conduction are present at specific frequencies. The full spectrum of frequencies forming the QRS complex has not been fully explored, and an upper limit of QRS frequencies is currently unknown. While the relative power