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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/sec. 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/sec) 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 zero (DC) to 10 Hz. The content of P wave is characterized by 5-30 Hz

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frequencies. The content of QRS usually contains within 8-50 Hz frequencies while abnormal ventricular conduction is characterized by high frequencies (above 70Hz), 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 to 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.

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 100Hz (“100 cycles per second”), high-frequency notching and slurring within QRS complex was 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

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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[11] et al, 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 (70-700Hz) 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 > 80Hz is less than 3%, by frequencies > 90Hz is less than 2%, and by frequencies > 100Hz 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 (150-250Hz) 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

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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 700Hz. 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 contribution of high QRS frequencies (above 70 Hz) is small, the clinical value of analyzing abnormal high-frequency QRS features is high. Further studies of QRS frequency content are needed.

Time-frequency analysis

The ECG signal has a change in both time-domain, and frequency-domain. Until 1950s-60s, ECG analysis was performed predominantly in the time-domain. To eliminate limitations of the one-dimensional analysis, conjoint time-frequency techniques are needed so that the evolution of ECG signal can be presented a function of both time and frequency. The Fourier transform became a very useful approach for frequency analysis in stationary conditions (e.g. on an averaged beat, and within QRS complex). However, overall ECG signal is non-stationary and multicomponent by nature. The choice of the proper time-frequency distribution is important, to reveal the multicomponent structure of biological signals, and to estimate an instantaneous frequency. Numerous time-frequency distributions for analysis of non-stationary biological signals have been developed, and many of them are known as the Cohen's Class [23]: the Wigner-Ville, The Choi-Williams, the Exponential T-distribution, the Hyperbolic T-distribution, the Born-Jordan, the Bessel, and the Periodogram. However, only a few of them have been applied to the ECG analysis[24] and primarily focused on the goal of beats discrimination, e.g. to discriminate normal sinus beats from premature ventricular contractions. Abeysekera [25] in 1991 applied Fast Fourier Transformation (FFT) to vectorcardiographic (VCG) loops with the goal to develop Fourier descriptors for automatic rhythm analysis.

While the exploration of the Cohen's Class time-frequency distributions did not result in the development of practically useful analytical applications in electrocardiology, the conjoint time-frequency analytical approach is an important step forward. Recently, two time-frequency analytical approaches showed the usefulness in ECG analysis: wavelet transformation[26; 27], and synchrosqueezing[28]. Synchrosqueezing transform provides

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adaptive time-frequency decomposition of multicomponent ECG signals. We previously applied synchrosqueezing for detection of P-wave and atrioventricular block[29]. Gramatikov and Iyer[30] used the continuous wavelet transform to characterize intra-QRS spectral changes. We recently developed a novel time-frequency analytical approach, which revealed inapparent ventricular conduction features in VCG QRS loops[1]. Further investigations of intraventricular conduction with applied conjoined time-frequency analytical approaches are needed.

Orbital frequency of vectorcardiographic loops: a novel analytical dimension

We developed an analytical approach, which brought a novel, previously unrecognized dimension in a time-frequency analysis of the ECG signal [1]. In addition to ECG signal analysis in the time and frequency domains, we added the extra dimension of three-dimensional space. Our approach to the time-frequency analysis of ventricular conduction is implemented in the analysis of three-dimensional QRS loops[1]. We introduced orbital frequency, which is a product of speed and curvature, as a novel three-dimensional characteristic of the QRS VCG loop (Figure 1). First investigations showed that measurements of orbital frequency across QRS time- and frequency-domain allowed nearly perfect discrimination and identification of the electrophysiological substrate of the life-threatening ventricular tachycardia[1]. Overall, our novel method performs conjoint analysis of the ECG signal in six dimensions: in the three space dimensions domain, time domain, and frequency domain.

Relative value of various QRS frequencies

As shown above, since the birth of the electrocardiology field investigators attempted to determine: which QRS frequencies are most useful for analysis? Different investigators had different answers to that question. Importantly, it should be considered that most of commercially available ECG devices routinely provide ECG signal with a passband up to 150 Hz. We refer to an excellent review of modern approaches to the QRS signal filtering, by Luo and Johnston[31]. Endocardial mapping of the left ventricle in patients with sustained ventricular tachycardia revealed that frequencies 40-500 Hz[32; 33] and especially 70-350 Hz[18] are especially helpful for identification of abnormal fractionated electrograms. Abboud [34] showed that a bandpass 150-250 Hz reveals a zone of reduced amplitude in high-frequency QRS complex during acute occlusion of the coronary artery. A substantial body of evidence exists regarding the usefulness of a 150-250Hz bandpass, summarized in the review by Tragardh and Schlegel [35].

Other investigators have demonstrated the usefulness of lower frequencies. Cain et al. [36] showed that the terminal QRS and ST segments from patients with sustained VT contained a 10- to 100-fold greater proportion of components in the 20-50 Hz range. QRS frequencies at the 24–80 Hz range have been found as the most informative in a recent study[30].

We believe that “the most informative” bandpass of QRS frequencies is different for different patients and depends on morphological and electrophysiological properties of an

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underlying substrate. Moreover, it could be dynamic and change over time in the same patient. The full spectrum of QRS frequencies should be explored in order to provide the most meaningful and complete information, as we recently showed[1]. For a future exploration of high frequencies of the QRS signal, it is important to record high-resolution ECG signal, to overcome the Nyquist limitation on detectable frequency[31].

Analog to Digital Conversion (ADC), Sampling frequency, and Nyquist frequency

The Nyquist frequency is a key concept in the ADC. The Nyquist frequency is half the sampling rate. A signal distortion, called aliasing, occurs at frequencies above the Nyquist frequency. To prevent aliasing interference, the low-pass filter must reject frequencies equal to and greater than the particular Nyquist frequency.

The semiconductor industry made major advances recently and introduced fast low-power 24 bit Sigma-Delta ADC with a dynamic range of more than 115 dB (> 19 bit effective resolution) and options for high sampling rates (up to 200 kHz). Use of such devices for ECG signal recording could bring unprecedented future discoveries. Upgrade of modern ECG manufacturing industry is warranted.

Summary

In summary, substantial scientific evidence has accumulated over more than 100 years on the importance of QRS frequency content for characterization of the arrhythmogenic electrophysiological substrate. However, it was only recently that opportunities for conjoint analysis of the ECG signal in multiple dimensions (domain of the three-dimensional space, time-domain, and frequency-domain) became available. The novel approach allows for non-invasive characterization of ventricular conduction properties, which otherwise are not seen on unfiltered ECG. Further studies of inapparent ventricular conduction are needed. Future potential applications of the novel method include risk stratification of sudden cardiac death, mapping of ventricular tachycardia and other cardiac arrhythmias for guidance of ablation, and assessment of ablation end-point.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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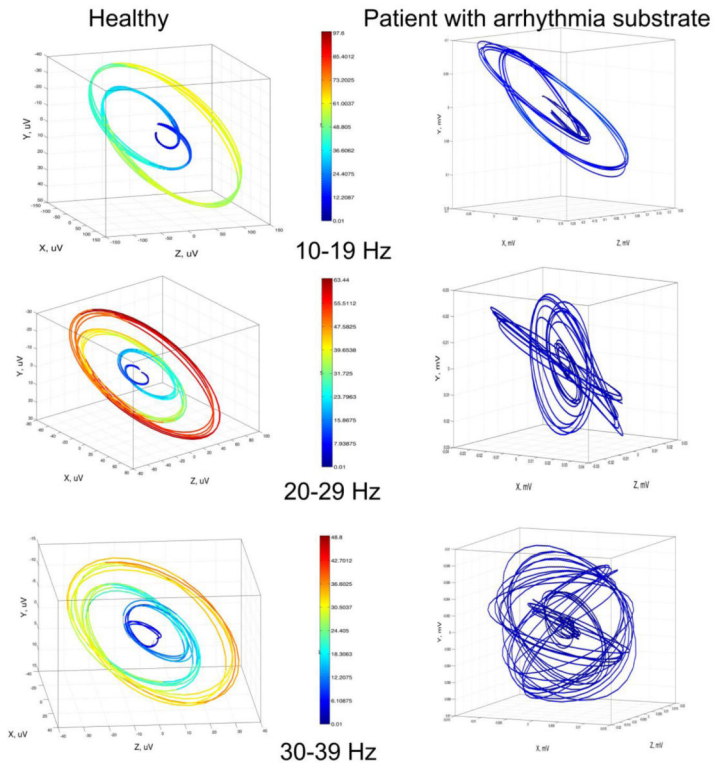

Figure 1.

Comparison of the speed and orbital frequency (product of speed and curvature) of filtered heart vector movement throughout the QRS in sinus rhythm in healthy subject (left column) and a patient with monomorphic ventricular tachycardia (right column). QRS loops of five sinus beats filtered at 10-19Hz, 20-29Hz, and 30-39Hz are shown. The color scale represents speed and is computed using the minimum and maximum velocity values as shown by the legend on each panel (blue = minimum speed; red = maximum speed).