A Software Platform for Comparative Analysis of Vectocardiograms in Pacemaker and CRT Optimization

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Abstract

Vectorcardiographic (VCG) analysis is becoming increasingly important in the assessment and follow-up of patients with pacemakers and cardiac resynchronization therapy (CRT) devices. However, the lack of practical tools for direct comparison of device configurations limits its routine clinical use. This study presents a custom software platform developed to enable side-by-side analysis of VCGs acquired before and after device reprogramming. The tool supports both native Frank VCGs and VCGs reconstructed from 12-lead ECGs using Dower and Kors transformation matrices, providing flexibility for diverse clinical workflows. Automated algorithms extract and compare key spatial parameters, including loop amplitudes, durations, and temporal dynamics. By offering quantitative and visual comparisons of device settings, the platform facilitates more objective, data-driven decisions during pacemaker and CRT optimization. Preliminary clinical use suggests the tool enhances workflow efficiency and supports improved patient outcomes.

1. Introduction

Cardiac pacemakers and cardiac resynchronization therapy (CRT) devices are cornerstones in the management of bradyarrhythmias and drug-refractory heart failure. Annually, hundreds of thousands of patients worldwide receive these implantable devices, which have been proven to improve survival, reduce heart failure hospitalizations, and enhance quality of life [1, 2]. The clinical efficacy of these therapies, however, is critically dependent on the precise programming of device parameters, particularly the atrioventricular (AV) and interventricular (VV) delays for CRT. The process of optimizing these settings remains a complex and often lengthy undertaking, typically involving multiple in-clinic visits where a clinician manually adjusts parameters and assesses the patient's acute response.

This traditional optimization process presents several significant challenges. It is inherently time-intensive, placing a considerable burden on both clinical resources and patient time. Furthermore, the reliance on manual adjustments guided by qualitative assessments of the 12-lead electrocardiogram (ECG)—such as QRS duration and morphology—has shown limited correlation with long-term clinical outcomes [3]. While echocardiography is widely used to assess mechanical dyssynchrony, it is time-consuming, requires significant operator expertise, and suffers from intra- and inter-observer variability, which has led to inconsistent results in major clinical trials [4,5]. The lack of a standardized, rapid, and quantitative method for comparing different device configurations makes it difficult to ensure that each patient receives the most hemodynamically advantageous settings, potentially contributing to the 30–40% non-response rate observed in CRT patients [6].

To address these limitations, there is a clear need for objective and efficient tools that can streamline the optimization workflow. The vectorcardiogram (VCG), derived from the standard 12-lead ECG using a mathematical transformation such as the inverse Dower matrix, offers a promising yet underutilized data source for this purpose [7]. The VCG provides a comprehensive three-dimensional representation of the heart's electrical activity [8]. Several studies have highlighted the value of VCG-derived parameters; for example, a larger QRS-loop area and a more organized loop morphology have been correlated with improved cardiac function and positive response to CRT [9, 10]. Unlike scalar ECG measurements, the VCG loop captures the entire ventricular activation sequence in 3D space, offering a more holistic view of electrical synchrony.

In this paper, we introduce a novel, Windows-based C++ software platform developed to facilitate the detailed and quantitative comparison of VCGs. A core feature of our platform is the ability to load and display two VCG recordings simultaneously, enabling a direct, side-by-side visual and quantitative comparison of loop characteristics under

different device configurations. By providing clinicians with a robust tool to analyze changes in VCG loop morphology, area, and orientation between two distinct settings, our platform aims to simplify the optimization process and enable a more data-driven approach to programming pacemaker and CRT devices. We hypothesize that this direct comparative tool can lead to more consistent and optimal clinical outcomes for patients.

2. Methods

The software platform is designed to process both native Frank vectorcardiograms (VCGs) and VCGs reconstructed from 12-lead electrocardiograms (ECGs) using transformation matrices. Two methods are supported for this purpose: the inverse Dower matrix [11] and the approach developed by Kors et al. [12]. These transformations derive the orthogonal X, Y, and Z components from Einthoven-based ECG signals, enabling spatial vectorcardiographic analysis. Their comparative performance has been evaluated in recent studies, including Vondrak et al. [13].

Upon acquisition, signals are segmented into eleven-second windows. From each segment, a median beat is extracted to serve as a noise-reduced baseline. Fully automated delineation algorithms are then applied to detect key fiducial points, such as the onset and offset of the P wave, QRS complex, and T wave. If ECG-derived data is used, the selected transformation matrix is applied prior to analysis.

The software also enables users to select specific beats—such as ectopic, premature, or paced complexes—for side-by-side comparison with the median beat. This functionality supports the assessment of beat-to-beat variability, conduction disturbances, and transient changes due to device programming.

From each VCG, the software extracts both standard and advanced temporal and spatial parameters. These include PR, QRS, and QT intervals; wave amplitudes in three axes; time-to-peak and time-to-descend values; and rise-to-fall time ratios. All measurements are computed in three-dimensional vector space to avoid distortion from planar projections.

The extraction and quantification of global electrical heterogeneity markers, including spatial QRS-T angle and sum absolute QRST integral (SAI QRST), were guided by methodologies validated in large-scale population studies such as ARIC and CHS [14]. All of these parameters can be exported as a structured .txt file for further analysis.

3. Results

The developed software is currently being implemented in clinical practice for the routine evaluation of patients with pacemakers and cardiac resynchronization therapy (CRT) devices. During standard patient visits, cardiologists follow a protocol that includes acquiring an ECG upon patient arrival and repeating the recording after adjustments to device settings. This enables immediate visualization of the electrical changes, particularly in the QRS loop morphology, resulting from the new configuration.

The platform facilitates a clear before-and-after comparison of vectorcardiographic features, helping clinicians assess the effectiveness of programming modifications. Figures 1 and 2 illustrate the software's graphical interface and core functionalities. In Figure 1, the platform is used to compare two VCG loops acquired from the same patient using the Frank lead system, highlighting morphological differences between two cardiac beats. In Figure 2, the comparison involves VCGs reconstructed from ECGs using two distinct transformation methods—Kors and Dower—demonstrating how the choice of transformation matrix can influence the resulting VCG and clinical interpretation.

4. Conclusion

As vectorcardiographic analysis gains increasing relevance in the evaluation and follow-up of CRT and pacemaker patients, the need for practical tools that support direct comparison of device settings has become evident. The software platform described in this study addresses this clinical gap by enabling detailed, side-by-side analysis of VCGs obtained before and after device reprogramming.

By incorporating both native Frank VCGs and ECG-transformed VCGs using Dower and Kors matrices, the platform offers flexibility for a range of clinical workflows. Its ability to perform automatic extraction and comparison of key spatial parameters—such as loop amplitudes and durations—enhances objectivity in the evaluation process. Overall, this tool supports more informed, data-driven decisions in the optimization of pacemaker and CRT therapy, potentially contributing to improved patient outcomes.

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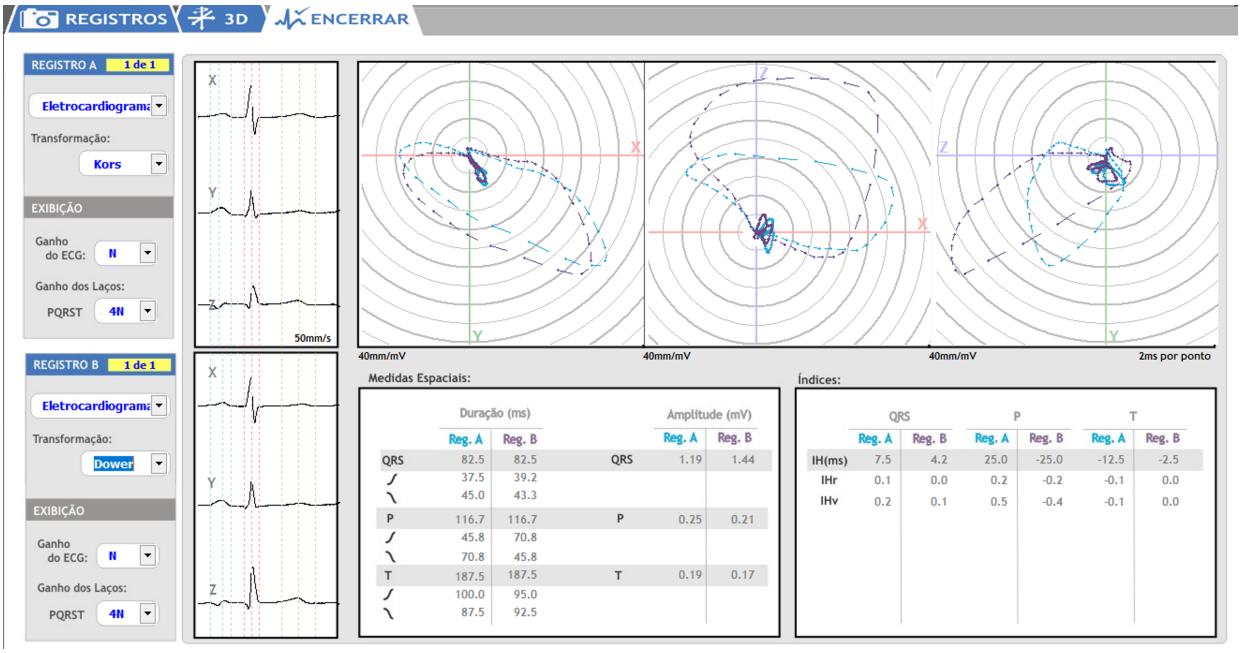

Figure 1. Software interface with comparison of the VCG of the same patient obtained by two different methods. The loops delimitation can be altered on the XYZ derivations view. The cubic meadurements such as QRS duration, amplitude, rise and fall times are automatically calculated as well as the ratio of rise time to duration.

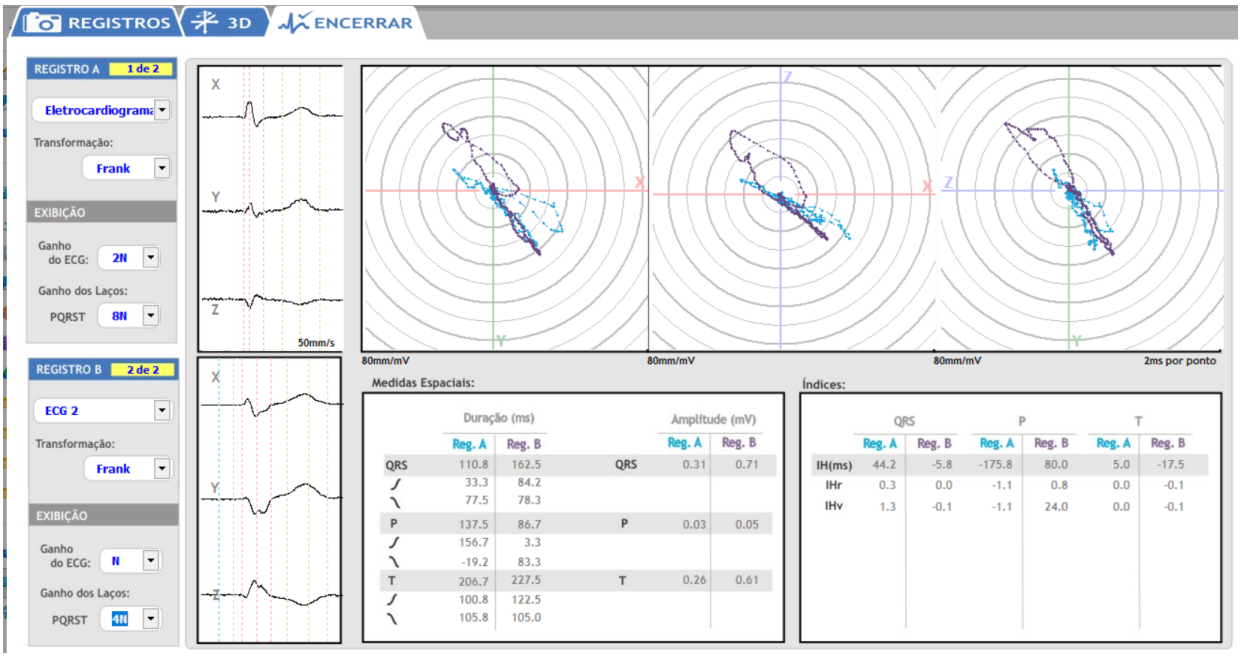

Figure 2. Software interface displaying a comparison of two consecutive beats recorded from the same patient using the Frank vectorcardiogram (VCG) system. The patient exhibits frequent ectopic beats. The interface highlights morphological differences between a typical beat and an ectopic beat, enabling precise visual assessment of beat-to-beat variability.

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