

Predicting the Left Ventricular Ejection Fraction Using Bimodal Cardiac Auscultation

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Abstract

Aims: Heart Failure (HF) is a global health challenge that is often associated with reduced left ventricular ejection fraction (EF). Current EF assessments rely on echocardiography exams performed by specialists. This study explores the feasibility of predicting EF using cardiac intervals derived from synchronous phonocardiography (PCG) and single-lead electrocardiography (ECG) recorded with a bimodal stethoscope.

Methods: 84 pairs of synchronous PCG and ECG signals were collected from 42 patients. Signal pairs were categorized into three different EF groups: EF <40%, EF 40-49% and EF ≥50%.

Results: Logistic regression revealed that the QS2 interval was a significant predictor of reduced ejection fraction, with $p = 0.0186$ for EF $\neq 40\%$ and $p = 0.0090$ for EF $\neq 50\%$. QT interval showed no predictive value. The Kruskal-Wallis test showed significant group differences for QS2 ($p=0.008$) and S1S2 ($p=0.009$), but not for QT ($p=0.299$) or QS1 ($p=0.673$). Mann-Whitney U-test confirmed that QS2 and S1S2 intervals differed significantly between EF.

1. Introduction

Worldwide the prevalence of heart failure (HF) is estimated to be around 64 million people. The prevalence of HF among adults is generally 1-2%, both globally and in Denmark [1], [2]. In Portugal, the prevalence is higher, with an estimated level of 4.36% [3]. The prevalence of HF increases significantly with age, and as the population is getting older, the numbers of HF patients is also expected to rise. A Portuguese study estimates that the number of HF will increase by 30% by 2035 [3]. Ischemic heart disease is the leading cause of death globally, and HF is frequently associated with this condition. Heart failure often develops as a consequence of prolonged ischemic heart disease, where the heart's muscles weaken after repeated episodes of reduced blood supply [4]. The worldwide healthcare burden related to HF is estimated to be 108 billion US dollars in direct and indirect costs. This represents around 1-2% of the total healthcare spending in

developed countries [5].

Patients referred for HF evaluation should undergo an echocardiography (Echo), which is performed by a cardiologist. A complete history is taken, which includes an assessment of the NYHA classification, objective findings, ECG, chest X-ray, any previous cardiovascular disease, lung function tests, and blood tests. It is recommended to take the NT-proBNP blood test [6].

The Echo is an important examination in the evaluation of HF, as it evaluates the hemodynamic effect and determines the severity. However, Echo requires specialist and equipment, limiting accessibility in some settings [7]. This study explores the feasibility of using a non-invasive, portable device, a bimodal stethoscope, which records synchronized phonocardiography (PCG) and single-lead electrocardiography (ECG) [8].

By analyzing time intervals such as QT, QS2, S1S2, and QS1 derived from these signals, the study aims to determine which intervals best correlate with ejection fraction (EF) levels, and whether these measures can support HF screening and monitoring outside of specialized clinical settings.

A prospective cohort study by Boudoulas et al. [10] investigated the role of QT>QS2 as a prognostic marker in patients with stable coronary artery disease following a prior myocardial infarction. The study included 100 patients, who were followed on average for 43 months. The results showed that patients with QT>QS2 had a significantly shorter 5-year survival rate, with a 35% survival rate compared to a 91% survival rate for patients without QT>QS2 [9]. The aim of this study was to explore if the ejection fraction can be predicted using the QT, QS2, QS1 and S1S2 intervals recorded by a bimodal stethoscope and, if so, which of the examined intervals provides the most reliable information to predict a reduced EF.

2. Methods

2.1. Study Population

The study is conducted with the cardiology department of Unidade Local de Saúde de Gaia/Espinho (ULSGE), Portugal. The population consists of hospitalized patients in the department of cardiology.

Inclusion criteria: All patients that were admitted to the department of cardiology during the period of the study, which was from the 1st of April 2022 until the 31st of march 2024. **Exclusion criteria:** Patients that were unable to comprehend the study and could not provide informed consent, to ensure ethical and legal compliance.

All patients enrolled in the study did it with voluntary consent, to maintain ethical standards per the Declaration of Helsinki and local regulations in the Portuguese law.

The project primarily enrolled patients with various cardiovascular conditions that were admitted for routine care or other specific cardiac assessments.

Although the study's screening tool focuses on heart diseases, including valvular conditions and arrhythmias, the inclusion of participants with a wide range of cardiac health issues contributed diverse data, and thereby increasing the study's applicability and generalizability.

2.2. Data Collection

To collect the data, the Rijuven Cardiosleeve was used. The Cardiosleeve is a digital stethoscope capable of simultaneously recording the heart sound and electrocardiogram [8]. All patients also underwent an echocardiographic examination, during which left ventricular ejection fraction was estimated using the biplane method. This measurement served as the reference standard in the study. PCG signals were collected at a sampling frequency of 3 kHz, whereas ECG signals were sampled at 500 Hz. PCG and ECG recordings were taken from the standard four auscultation spots; each recording lasted 30 seconds.

2.3. Data Processing

For visualization of the signals, MATLAB was used. A GUI was used to provide an overview of the median heartbeat of the synchronized PCG and ECG signals. This allowed faster and more manageable manual review of multiple signals.

2.3.1. Quality of Data

The quality of the signals was manually evaluated using a tailored MATLAB GUI. This allowed for simultaneous visual inspection of the PCG and ECG Signals. Due to variability in signal quality, it was not feasible to utilize data from all the auscultation spots for each patient. Additionally, many of the recordings had a quality that was too poor to effectively visualize them in the GUI. Consequently, some signals were excluded from the analysis: some were excluded due to too much noise to identify the fiducial points; some signals that did not provide a clear PCG and ECG; the remaining exclusions

were signals with such poor quality that they could not be uploaded in the GUI. A total of 84 recordings were selected for inclusion in the study. Of these, four originated from patients with reduced ejection fraction ($EF < 40\%$), 25 from patients with mildly reduced ejection fraction ($EF 40-49\%$), and 55 from patients with preserved ejection fraction ($EF \geq 50\%$). Among the selected recordings, some were relatively easy to interpret, others were significantly affected by noise.

2.3.2. Annotation of QT and S1, S2 Heart Sounds

When annotating the Q, T, S1 and S2 the MATLAB GUI was used (see Figure 1). The mean heartbeats were chosen as the ones to conduct the intervals from for each recording. The annotation was performed by a single person.

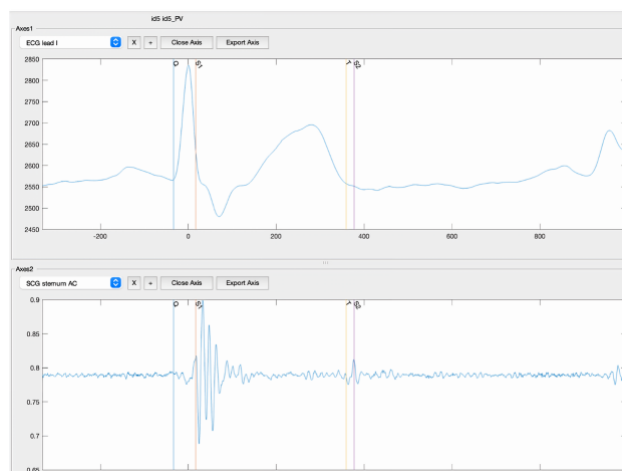


Figure 1: Example of Manual Annotation, patient 5, Pulmonary Valve.

The annotation process followed a structured set of steps to ensure data integrity and consistency. First, each signal was evaluated to confirm that the quality was sufficient to accurately identify the relevant fiducial points. Second, only signals from patients with documented ejection fraction (EF) values were included. Once these criteria were met, manual annotation of the Q and T waves (from the ECG) as well as the S1 and S2 heart sounds (from the PCG) was initiated.

2.4. Interval Measurements

The QT, QS2, S1S2, and QS1 intervals were identified using manual annotation in MATLAB.

QT interval: Represents the duration of electrical systole, measured from the onset of the Q wave to the end of the T wave on the ECG. It reflects the total time of

ventricular depolarization and repolarization [10].

QS2 interval: Refers the electromechanical systole, measured from the onset of the Q wave to the second heart sound (S2). It includes both the electrical activation and the mechanical contraction of the ventricles until aortic valve closure [11].

S1S2 interval: Corresponds to the mechanical systole, measured between the first (S1) and second (S2) heart sounds. This interval represents the duration of ventricular contraction between mitral/tricuspid valve closure (S1) and aortic/pulmonary valve closure (S2) [11].

QS1 interval: Refers to the electromechanical delay, measured from the onset of the Q wave to the first heart sound (S1). This interval indicates the time between the start of ventricular depolarization and the onset of mechanical contraction (valve closure) [11]. Q onset was identified at the beginning of ventricular depolarization, and T end was defined as the termination of ventricular repolarization. S1 onset was placed at atrioventricular valve closure, and S2 onset was placed at aortic and pulmonary valve closure.

3. Results

3.1. Statistical Methods

Two statistical approaches were applied in this study: A logistic regression and a Kruskal-Wallis test. Logistic regression was used to explore the predictive value of two selected intervals (specifically QT and QS2) in relation to EF outcomes, as logistic regression is appropriate for modeling binary outcomes, such as $EF \leq 40\%$ and $EF > 50\%$, based on continuous independent variables.

Initially, a one-way ANOVA was considered to assess differences in the dependent variables across the three EF groups. However, results from the Shapiro-Wilk normality test indicated that several variables were not normally distributed. To ensure consistency and methodological robustness, the Kruskal-Wallis test was used. This non-parametric test is well-suited for comparing multiple groups when the assumption of normality is not met.

3.2. Statistical Results

The mean and standard deviation of the considered cardiac intervals in the three EF groups are reported in Figure 2.

Logistic regression analysis including both QT and QS2 intervals showed that patients could be separated by ejection fraction below or above 40% ($p = 0.00112$) and 50% ($p = 0.0197$). In both models, QS2 was the only significant individual predictor ($p = 0.0186$ for $EF \leq 40\%$ and $p = 0.0090$ for $EF > 50\%$), whereas the QT interval showed no significant predictive value.

The Kruskal-Wallis test revealed statistically significant group differences for the S1S2 interval ($p = 0.009$) and QS2 interval across at least two of the EF groups. Post hoc analysis using the Mann-Whitney U test identified significant differences in the QS2 interval between patients with $EF < 40\%$ and those with $EF \geq 50\%$ ($p = 0.005$), as well as between $EF < 40\%$ and $EF 40-49\%$ ($p = 0.010$). Similarly, the S1S2 interval differed significantly between $EF < 40\%$ and $EF 40-49\%$ ($p = 0.009$), and between $EF < 40\%$ and $EF \geq 50\%$ ($p = 0.002$).

In contrast, the QS1 and QT intervals did not show significant group differences and were not identified as discriminative features.

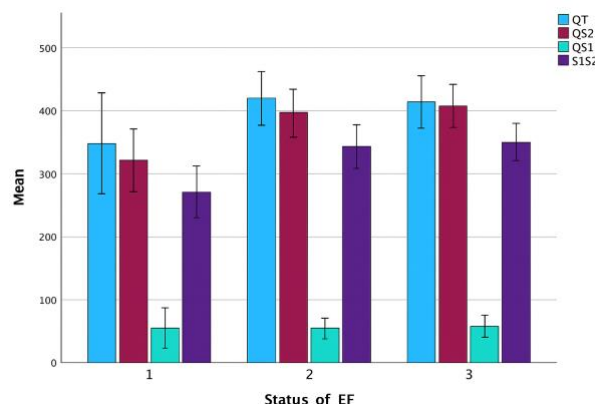


Figure 2: Mean and standard deviation of the cardiac time intervals QT, QS2, QS1, and S1S2 for three patient groups classified according to ejection fraction (EF): $EF < 40\%$ (case 1), $40\% < EF < 50\%$ (case 2), and $EF > 50\%$ (case 3). Error bars represent standard deviation.

4. Discussion

The findings support QS2 and S1S2 as promising non-invasive markers for EF prediction. These results align with prior studies demonstrating the relevance of electromechanical systole (QS2) in systolic function evaluation.

Furthermore, a recent study by Guo et al. validated an artificial intelligence-based algorithm that uses a digital stethoscope to combine ECG and heart sound data in order to identify patients with reduced left ventricular ejection fraction ($EF \leq 40\%$) [12]. The study included 2,960 patients from four U.S. centers and demonstrated high diagnostic accuracy (AUROC 0.85), with a negative predictive value of 98%. This technology offers a non-invasive, scalable solution for the early detection of asymptomatic systolic dysfunction and may support earlier intervention and improved patient outcomes, particularly in primary care and low-resource setting [12]. These findings are consistent with our own and highlight the potential of using electrophysiological and acoustic signals

for predictive diagnostics.

5. Conclusion

QS2 and S1S2 intervals measured with a bimodal stethoscope show potential as non-invasive EF predictors. This method may facilitate screening and monitoring of HF patients, especially where echocardiography is not available.

Of particular relevance, electromechanical assessment enabled by synchronous PCG and ECG recordings is shown to provide more accurate information regarding the cardiac activity with respect to single modalities.

Acknowledgments

This work is co-financed by Component 5 - Capitalization and Business Innovation, integrated in the Resilience Dimension of the Recovery and Resilience Plan within the scope of the Recovery and Resilience Mechanism (MRR) of the European Union (EU), framed in the Next Generation EU, for the period 2021 - 2026, within project HfPT, with reference 41.

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