Vectorcardiographic QRS area as a novel predictor of response to cardiac resynchronization therapy

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Abstract

Background: QRS duration and left bundle branch block (LBBB) morphology are used to select patients for cardiac resynchronization therapy (CRT). We investigated whether the area of the QRS complex (QRS\textsubscript{AREA}) on the 3-dimensional vectorcardiogram (VCG) can improve patient selection.

Methods: VCG (Frank orthogonal lead system) was recorded prior to CRT device implantation in 81 consecutive patients. VCG parameters, including QRS\textsubscript{AREA}, were assessed, and compared to QRS duration and morphology. Three LBBB definitions were used, differing in requirement of mid-QRS notching. Responders to CRT (CRT-R) were defined as patients with ≥15% reduction in left ventricular end systolic volume after 6 months of CRT.

Results: Fifty-seven patients (70%) were CRT-R. QRS\textsubscript{AREA} was larger in CRT-R than in CRT non-responders (140 ± 42 vs 100 ± 40 μVs, \(p < 0.001\)) and predicted CRT response better than QRS duration (AUC 0.78 vs 0.62, \(p = 0.030\)). With a 98 μVs cutoff value, QRS\textsubscript{AREA} identified CRT-R with an odds ratio (OR) of 10.2 and a 95% confidence interval (CI) of 3.4 to 31.1. This OR was higher than that for QRS duration \(\leq 156\) ms (OR = 2.5; 95% CI 0.9 to 6.6), conventional LBBB classification (OR = 5.5; 95% CI 0.9 to 32.4) or LBBB classification according to American guidelines (OR = 4.5; 95% CI 1.6 to 12.6) or Strauss (OR = 10.0; 95% CI 3.2 to 31.1).

Conclusion: QRS\textsubscript{AREA} is an objective electrophysiological predictor of CRT response that performs at least as good as the most refined definition of LBBB.

Condensed abstract: In 81 candidates for cardiac resynchronization therapy (CRT) we measured the area of the QRS complex (QRS\textsubscript{AREA}) using 3-dimensional vectorcardiography. QRS\textsubscript{AREA} was larger in echocardiographic responders than in non-responders and predicted CRT response better than QRS duration and than simple LBBB criteria. QRS\textsubscript{AREA} is a promising electrophysiological predictor of CRT response.

Keywords: Cardiac resynchronization therapy; QRS area; Vectorcardiography

Introduction

Cardiac resynchronization therapy (CRT) is recommended in patients with left bundle branch block (LBBB) conduction disturbances and persistent systolic heart failure despite optimal medical therapy. By simultaneous stimulation of the right (RV) and left (LV) ventricles the abnormal ventricular activation is (partly) resynchronized. This electrical resynchronization results in better LV pump function and reverse ventricular remodeling on the long term with a decrease in LV volumes, improving exercise capacity, and reducing heart failure hospitalizations and mortality [1,2].

Although the effects of CRT in large clinical trials are impressive on a group level, benefits for the individual patient vary considerably and are hard to predict. Up to half...
of the patients do not show a significant reduction in LV end systolic volume (LVESV) and around 30% of patients do not show clinical improvement [3]. Thus, to avoid invasive procedures with the risk of complications and the unnecessary use of expensive products, a reliable tool for prediction of responders to CRT is needed.

Many different strategies have been proposed, including several echocardiographic parameters [4], but up to now the ECG parameters QRS duration and QRS morphology are most widely accepted [5–8], emphasizing the importance of a good electrical substrate for this electrical therapy. Consequently, American and European guidelines for clinical decision making to implant a CRT device have included these electrical markers, i.e. QRS duration ≥150 ms with LBBB morphology for class 1A recommendation [9,10]. However, the definition of complete LBBB from the 12-lead ECG varies and the most appropriate definition is still under debate [11]. Recently, Strauss et al. [12] suggested to include the presence of mid-QRS notching or slurring. Some of their suggestions were subsequently incorporated in the American guidelines for identification of LBBB [13]. Besides the dissimilarity in how many and which leads should display QRS notching or slurring, the classification of the presence of “slurring” seems a subjective task.

We hypothesized that the QRS area (QRS\textsubscript{AREA}) from the 3-dimensional (3D) vectorcardiogram (VCG), which combines QRS duration and electrical force of ventricular activation, improves prediction of the response to CRT in comparison to QRS duration on the ECG alone. Moreover, QRS\textsubscript{AREA} is a continuous variable that is independent on the specific definitions of LBBB.

To this purpose we compared the predictive power of QRS\textsubscript{AREA} to the conventional electrical markers QRS duration and morphology, the latter being specified using multiple LBBB criteria, prospectively in a cohort of CRT patients.

**Materials and methods**

**Patients**

Patients with heart failure scheduled for implantation of a CRT device (CRT-P or CRT-D) at the Maastricht University Hospital between September 2010 and June 2012 were prospectively approached to participate in this study (n = 138). After exclusion of patients with previous RV pacing (n = 22) or an intrinsic QRS duration <120 ms (n = 13), 103 patients were included. The study was performed according to the principles of the Declaration of Helsinki and approved by the ethics committee of Maastricht University Hospital. All participants gave fully informed written consent prior to investigation.

**Study design**

A standard 12-lead electrocardiogram (ECG) and a 3D-VCG were recorded the day before CRT device implantation with patients at rest and in supine position.

The ECG was recorded at a paper speed of 25 mm/s and a scale of 10 mm/mV. QRS duration on the ECG was determined using the automatic calculated value given by the ECG equipment after confirmation of correctness. LBBB was classified by a single investigator (CvD), who was blinded to the echocardiographic outcome, according to three different definitions.

\[\text{LBBB}_1\] QRS duration ≥130 ms, rS or QS pattern in lead V\textsubscript{1}, absence of q-waves in V\textsubscript{5−V6} (conventional criterion) [6].

\[\text{LBBB}_2\] QRS duration ≥130 ms, rS or QS pattern in lead V\textsubscript{1}, intrinsicoid deflection in lead V\textsubscript{6} ≥60 ms, mid-QRS notching or slurring in 2 or more contiguous leads of V\textsubscript{1}, V\textsubscript{2}, V\textsubscript{5}, V\textsubscript{6}, I and aVL (according to Strauss et al. [12]).

\[\text{LBBB}_3\] QRS duration ≥130 ms, rS or QS pattern in lead V\textsubscript{1}, intrinsicoid deflection in lead V\textsubscript{6} ≥60 ms, broad notched or slurred R wave in leads V\textsubscript{5}, V\textsubscript{6}, I as well as aVL (according to American guidelines) [13].

The 3D-VCG was recorded the day before CRT device implantation using 8 electrodes positioned according to the modified Frank orthogonal lead system (X, Y and Z; Coronet II System, Ortivus AB, Danderyd, Sweden) at a sampling frequency of 500Hz for 5 minutes and averaged over one minute. The VCGs were analyzed offline using customized software [14]. The magnitude and direction of the maximum QRS vector in space were expressed as amplitude (QRS\textsubscript{AMPL}; mV), azimuth (angle in the transversal plane with backward vector direction being negative; degrees) and elevation (angle in craniocaudal direction with upward vector directions being >90\textdegree; degrees). QRS-T angle is the 3D-angle between maximum QRS and T vector in the preferential planes of the QRS and T vector loops. The QRS area (QRS\textsubscript{AREA}; μVs) was assessed as the “3D area” between the ventricular deflection curve and the baseline from the beginning to the end of the QRS complex (J-point) in X, Y and Z direction, and calculated as (QRS\textsubscript{x} + QRS\textsubscript{y} + QRS\textsubscript{z})\textsuperscript{1/2}; Fig. 1).

Ischemic etiology of heart failure was defined as presence of delayed enhancement on cardiac magnetic resonance imaging, irreversible perfusion defects on myocardial thallium scans or untreated >70% stenosis in a coronary artery according to coronary angiograms.

Echocardiography (ie33 systems, Philips Medical Systems, Best, the Netherlands) was performed the day before device implantation as well as at follow up 6 months later. CRT responders (CRT-R) and non-responders (CRT-NR) were defined as patients with ≥15% and <15% reduction in LVESV respectively, as determined using the biplane method of disks (modified Simpson’s method) after 6 months of CRT. In 26 patients the apical 2-chamber view was of poor quality and volumetric response was determined solely on the apical 4-chamber view. Assessors of echocardiography and vectorcardiography were blinded to the results from the other analyses.

**Statistical analysis**

Statistical analysis was performed using IBM SPSS Statistics software version 20 (SPSS Inc, Chicago, Illinois)
and MedCalc Software version 12.7.5 (MedCalc Software bvba, Ostend, Belgium). Continuous variables were presented as mean ± standard deviation (SD) or as median with interquartile range [IQR] in case of non-normal distribution; categorical variables as number (percentage). Linear correlations between different predictors and change in LVESV were evaluated by Pearson’s correlation coefficient. Comparison between CRT-R and CRT-NR was performed by Students’ T-tests or Mann–Whitney U test as appropriate (continuous variables) and χ^2 test (categorical variables). The classification performance of electrical parameters in identifying CRT response was evaluated by receiver operating characteristic (ROC) curve analysis. The significance of the difference in classification performance between parameters was evaluated by comparing the areas under the ROC curve (AUC) with the method proposed by DeLong et al. [15]. Continuous variables were dichotomized for comparison with discrete parameters by computing cut-off values with maximal sum of sensitivity and specificity. Subsequently, odds ratios (OR), sensitivity, specificity, positive predictive value (PPV) and negative predictive values (NPV) were calculated for all parameters. Differences were considered statistically significant at a two-sided p-value of 0.05.

Results

All patients underwent standard CRT device implantation with an RV lead implanted most frequently in the RV apex...
and the LV lead according to coronary venous anatomy at a position with good stability, pacing thresholds and absence of phrenic nerve stimulation. LV and RV lead positions were determined by lateral and frontal chest radiographs; Table 1. Optimization of stimulation intervals was performed according to the attending cardiologists’ decision.

After exclusion due to unsuccessful LV lead implantation (n = 10), atrial fibrillation with <90% biventricular pacing at follow-up (n = 2), missing echocardiographic evaluation at 6 months follow-up (n = 7), and impossible VCG analyses due to technical disturbances or multiple ectopic beats (n = 3), 81 patients were included for analyses.

Twenty-four patients (30%) were classified as CRT-NR. Baseline characteristics did not differ between CRT-R and CRT-NR except for ischemic etiology of heart failure which was more common in the CRT-NR group and the LV lead according to coronary venous anatomy at a position with good stability, pacing thresholds and absence of phrenic nerve stimulation. LV and RV lead positions were determined by lateral and frontal chest radiographs; Table 1. Optimization of stimulation intervals was performed according to the attending cardiologists’ decision.

After exclusion due to unsuccessful LV lead implantation (n = 10), atrial fibrillation with <90% biventricular pacing at follow-up (n = 2), missing echocardiographic evaluation at 6 months follow-up (n = 7), and impossible VCG analyses due to technical disturbances or multiple ectopic beats (n = 3), 81 patients were included for analyses.

Twenty-four patients (30%) were classified as CRT-NR. Baseline characteristics did not differ between CRT-R and CRT-NR except for ischemic etiology of heart failure which was more common in the CRT-NR group and the interventricular mechanical delay (IVMD) which was larger in the CRT-R group (Table 1).

**ECG and VCG parameters in responders and non-responders**

Typical vector loops in the frontal and transversal planes and corresponding ECGs for a CRT-NR and a CRT-R are shown in Fig. 1. The narrow vector loops of the CRT-R were characterized by a dominant vector amplitude in the transversal plane, clearly pointing to the back of the patient.

Baseline QRS duration, QRS\_AMPL and QRS\_AREA were all significantly larger in the CRT-R compared to the CRT-NR group, the difference between the groups being more pronounced for the VCG parameters (Table 2, Fig. 2).

**Correlation between ECG and VCG parameters and volumetric CRT response**

Using LVESV as a continuous variable, an inverse correlation was observed between QRS\_AMPL and QRS\_AREA and the percentage change in LVESV at 6 months of CRT (r = -0.54 and r = -0.57 respectively). These correlations were stronger than the correlation between QRS duration and change in LVESV (r = -0.20; Fig. 2).

**Predictive value of ECG and VCG parameters for CRT response**

In Fig. 3, ROC curves are displayed, showing the abilities of QRS duration, QRS\_AMPL and QRS\_AREA to predict CRT-R. The area under the ROC curve was largest for QRS\_AREA (AUC = 0.78), followed by QRS\_AMPL (AUC = 0.71) and QRS duration (AUC = 0.62). The AUC for QRS\_AREA was significantly larger than for QRS duration (p = 0.030), indicating a more accurate prediction of CRT response. Using a cutoff value for QRS\_AREA of 98 μVs, the odds ratio for predicting CRT response was much higher (OR = 10.2; 95% confidence interval (CI) 3.4 to 31.1) than for QRS duration >156 ms (OR = 2.5; 95% CI 0.9 to 6.6), LBBB\_1 (OR = 5.5; 95% CI 0.9 to 32.4) and LBBB\_2 (OR = 4.5; 95% CI 1.6 to 12.6), while LBBB\_3 had a comparable OR (OR = 10.0; 95% CI 3.2 to 31.1; Table 3).

QRS duration >156 ms falsely diagnosed 23 patients as CRT-NR (60% sensitivity and 63% specificity; Table 4 and Fig. 3). In comparison, QRS\_AREA >98 μVs only falsely diagnosed 8 patients as CRT-NR (86% sensitivity and 63% specificity).
specificity). The sum of sensitivity and specificity in predicting CRT-R was highest for QRS\_AREA > 98 \mu Vs.

**QRS\_AREA in relation to other markers and different patient characteristics**

Fig. 4 shows plots of QRS\_AREA versus QRS duration. The figure depicts that at a given QRS duration patients with a LBBB\_2 morphology displayed larger QRS\_AREA compared to those with non-LBBB\_2 morphologies. Similarly, among LBBB patients, QRS\_AREA was smaller in patients with an ischemic etiology of heart failure compared to those with a non-ischemic etiology. Furthermore, in patients with non-LBBB and ischemic etiology of heart failure, QRS duration may be prolonged without an increase in QRS\_AREA. Overall, QRS\_AREA was significantly smaller in patients with an ischemic etiology of heart failure (108 ± 39 \mu Vs vs 148 ± 43 \mu Vs, \( p < 0.001 \)). QRS\_AREA was not significantly different in males versus females (123 ± 43 \mu Vs vs 137 ± 48 \mu Vs, \( p = 0.183 \)), and not related to age (\( r = -0.15 \), \( p = 0.095 \)) or BMI (\( r = -0.17 \), \( p = 0.060 \)).

**Discussion**

The present prospective study demonstrates that the VCG parameter QRS\_AREA predicts volumetric CRT response at 6 months better than QRS\_AMPL or the presence of conventionally defined LBBB morphology. Moreover, the predictive power of QRS\_AREA is comparable to that of the most refined definition of LBBB, while it has the advantage of being objectively quantifiable as a continuous parameter.

QRS\_AREA as a predictor of response to CRT

Strong unopposed electrical forces, generated within the heart, are the likely underlying mechanism of a large QRS\_AREA. This is typically the case in dyssynchronous ventricular activation like LBBB, where ventricular activation wavefronts propagate to the left and back of the patient.
without simultaneous cancellation from wavefronts to the right and front of the patient [16]. This idea is supported by a study demonstrating that a larger QRS integral obtained with 120-channel body surface imaging strongly correlated to the presence of interventricular dyssynchrony obtained by Doppler echocardiography [17]. However, these investigators found that there was no standard body surface ECG lead to use for investigation of the QRS integral, because of dependency on the mean electrical axis of the heart. QRS\textsubscript{AREA}, which is the 3D-VCG QRS integral, can overcome this problem, because it is independent of QRS axis. According to a recent study using the same methodology as we employed, the average QRS\textsubscript{AREA} in healthy adult subjects was found to be 34 $\mu$Vs [18], a value of only one third of that in LBBB. Moreover, several studies have provided evidence that the more dysynchronous the baseline situation (especially LBBB), the better the substrate for CRT [19,20].

On the other hand, QRS\textsubscript{AREA} is smaller in patients with an ischemic etiology of heart failure and this etiology is known to decrease the chance of response to CRT. The lower QRS\textsubscript{AREA} in these hearts may be explained by the presence of non-conducting fibrotic tissue which also decreases the amount of tissue that can be recruited by CRT. Similarly, a lower QRS\textsubscript{AREA} may arise from consequences of severe hypertrophic remodeling such as electrical uncoupling between cells as a consequence of fibrosis or deranged expression or location of connexins [21]. These considerations might explain the power of QRS\textsubscript{AREA} for prediction of CRT response, but more research is required to better understand all determinants of QRS\textsubscript{AREA}.

**QRS\textsubscript{AREA} is a stronger predictor of CRT response as compared to QRS duration and LBBB morphology**

In the present study, an optimal cutoff value for QRS duration of $>156$ ms was calculated, close to the value used in large clinical trials (150 ms) [5,7,8]. However, we found that the power to predict CRT response was less than using QRS\textsubscript{AREA} $>98$ $\mu$Vs. This difference may be explained because QRS duration only includes the time of depolarization, while QRS\textsubscript{AREA} also reflects the electrical substrate for CRT response, as discussed above [22].

Recently, several studies have already reported that a LBBB morphology on the ECG is a stronger predictor of CRT response than QRS duration [6–8] and this is now incorporated in the current guidelines for class 1A recommendation [9,10]. However, until now conventional criteria for the definition of complete LBBB were used, which may include patients with a combination of LV hypertrophy, LV enlargement and incomplete LBBB [23], thus patients that possibly lack an ideal electrical substrate for resynchronization therapy. In addition, none of the conventional definitions have incorporated the presence of mid-QRS notching or slurring in 2 or more contiguous leads ($V_1$, $V_2$, $V_5$, $V_6$, $I$ and aVL) as suggested by Strauss et al. [12]. This refinement of the definition of LBBB morphology has shown to significantly improve the performance of predicting CRT response and clinical outcome as compared to the conventional definition [24,25]. In the present study, the use of a definition of LBBB that includes the presence of mid-QRS notching or slurring according to Strauss et al. appeared to be more accurate in predicting CRT response than the presence of QRS notching or slurring according to American guidelines or the conventional definition of LBBB. However, the predictive power of even the most refined LBBB definition was not better than having a QRS\textsubscript{AREA} of $>98$ $\mu$Vs. Though LBBB and QRS\textsubscript{AREA} $>98$ $\mu$Vs were strongly related to each other, the benefit of using QRS\textsubscript{AREA} may be the objective measurement, avoiding the subjective interpretation of presence of notching or slurring and the dependence on correct ECG lead positioning. Moreover, it provides a continuous measurement, making it possible to adapt the cutoff value according to the desired sensitivity and specificity. If an almost 100% specificity is wanted (i.e. no non-responders), a high cutoff value for QRS\textsubscript{AREA} should be applied.

**Potential clinical implications**

VCG is an easy and non-invasive technique. While we used a dedicated 3D-VCG system in the present study, most commercially available ECG machines have algorithms to construct VCGs using the inverse Dower or Kors’ regression transformation [18,26]. From this, an automatic calculated QRS area can be generated. However, the accuracy of the inverse transformations has yet to be demonstrated for patients with heart failure and wide QRS complex. Furthermore, the present study emphasizes the importance of including mid-QRS notching or slurring in the criteria for LBBB, especially when present in 2 or more contiguous leads of $V_1$, $V_2$, $V_5$, $V_6$, $I$ and aVL.

**Limitations**

Although the number of patients included in this single center study is modest and too small for subgroup analyses, this is to our knowledge, the first study investigating 3D-
VCG derived parameters as predictors of response to CRT. Assessment of LBBB was performed by a single reviewer, and an independent training and test set for the calculation of a cutoff value for QRS\_AREA was lacking. Multicenter prospective studies with a larger amount of patients are required to confirm our results. These larger studies should also search for confirmation of the predictive power of QRS\_AREA with regard to clinical outcome, hospitalization admissions and survival rate.

**Conclusion**

QRS\_AREA is a more powerful predictor of CRT response compared to QRS duration or conventionally defined LBBB morphology. Since it can be automatically computed, this parameter can be easily applied in daily clinical practice, thereby better identifying appropriate candidates for CRT and potentially preventing ineffective, invasive and costly CRT device implantations.

**What is new?**

- The best definition for predicting CRT response includes mid-QRS notching in \(\geq 2\) leads contiguous leads of V\(_1\), V\(_2\), V\(_5\), V\(_6\), I and aVL.
- Such LBBB definition improves the selection of patients that respond to CRT by a factor of 4 compared to using QRS duration \(\leq 150\) ms and by a factor 2 as compared to conventional LBBB definitions.
- Selection of CRT candidates with good response is at least as good with the objective and direction insensitive QRS\_AREA, derived from the VCG.
- 3D VCG is a promising tool for better application of CRT.

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**Author contribution**

Van Deursen: data analysis, drafting article; Vernooy: critical revision, data analysis; Dudink: data analysis; Bergfeldt: critical revision; Crijns: critical revision; Prinzen: funding, critical revision and final approval of article; Liliane Wecke: concept development, drafting, final approval.

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**References**


**Fig. 4.** QRS\_AREA plotted against QRS duration for patients without (left) and with (right) LBBB.2 morphology, and subdivided into presence of ischemic etiology of heart failure (ICM; plus sign) or non-ischemic etiology of heart failure (NICM; hyphen). Regression lines are given for subgroups. Note that among patients with non-LBBB and ICM, the QRS duration can prolong without an increase in QRS\_AREA. In LBBB patients, QRS\_AREA was smaller in patients with ICM compared to those with NICM.


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