Automatic QRS Selvester scoring system in patients with left bundle branch block

Xiaojuan Xia1*, Björn Wieslander2, David G. Strauss3, Galen S. Wagner4, Wojciech Zareba1, Arthur J. Moss1, and Jean-Philippe Couderc1

1Heart Research Follow-Up Program, Cardiology Division, University of Rochester Medical Center, 265 Crittenden Boulevard, PO Box 653, Rochester, NY 14642, USA; 2Clinical Physiology, Karolinska Institute and Karolinska University Hospital, Stockholm, Sweden; 3Office of Science and Engineering Laboratories, Center for Devices and Radiological Health, United States Food and Drug Administration, Silver Spring, MD, USA; and 4Duke Clinical Research Institute, Duke University, Durham, NC, USA

Received 30 July 2014; accepted after revision 25 January 2015; online publish-ahead-of-print 23 March 2015

Published on behalf of the European Society of Cardiology. All rights reserved.

doi:10.1093/europace/euv040

Europace (2016) 18, 308–314

Introduction

The Selvester QRS scoring system is a scoring system based on quantitative criteria from the standard 12-lead electrocardiogram (ECG), which estimates the size and location of myocardial scar in the left ventricle. It was derived from a computer simulation of the electrical activation sequence of the human heart1 and was validated through comprehensive anatomic correlations.2–5 The QRS scores applying this rigorous method provided strong prognostic information on survival rate for patients with coronary artery disease6; also the scores were correlated with left ventricular (LV) function after myocardial infarction (MI).7 In 2008, the scoring system was expanded for application in the presence of multiple inter-ventricular conduction abnormalities8; including complete left bundle branch block (LBBB). Automation of the scoring system could facilitate the clinical use of this technique which requires a set of multiple QRS patterns to be identified and measured.

Methods and results

We developed a series of algorithms to automatically detect and measure the QRS parameters required for Selvester scoring. The ‘QUantitative and Automatic REport of Selvester Score’ was designed specifically for the analysis of ECGs from patients meeting new strict criteria for complete LBBB. The algorithms were designed using a training (n = 36) and a validation (n = 180) set of ECGs, consisting of signal-averaged 12-lead ECGs (1000 Hz sampling) recorded from 216 LBBB patients from the MADIT-CRT. We assessed the performance of the methods using expert manually- adjudicated ECGs. The average of absolute differences between automatic and adjudicated Selvester scoring was 1.2 ± 1.5 points. The range of average differences for continuous measurements of wave locations and interval durations varied between 0 and 6 ms. Erroneous detection of Q, R, S, R’, and S’ waves (oversensed or missed) were 3, 1, 1, 16, and 6%, respectively. Seven percent of notches detected in the first 40 ms were misdectected.

Conclusion

We propose an efficient computerized method for the automatic measurement of the Selvester score in patients with the strict LBBB.

Keywords

Selvester QRS scoring system • Left bundle branch block • Electrocardiography

7 In 2008, the scoring system was expanded for application in the presence of multiple inter-ventricular conduction abnormalities8; including complete left bundle branch block (LBBB) based on a new ‘strict’ criteria.9,10 The QRS scoring system for patients with ‘ECG confounding factors’ (i.e. ventricular hypertrophy and bundle branch/fascicular blocks) has been tested for quantifying scar location and size in comparison with cardiac magnetic resonance imaging with late gadolinium enhancement.10,11 Recently, this new version of the QRS scoring was shown to be associated with a predictive value for detrimental response to cardiac resynchronization therapy (CRT).12 Importantly, the definition of LBBB for the Selvester scoring method is different from the standard clinical definition, i.e. QRS duration ≥ 140 ms (men) or 130 ms (women), QS or rS in V1 and V2, and along with mid-QRS notching/slurring in ≥2 contiguous leads9 (see left panel of Figure 1) vs. the World Health Organization LBBB definition (QRS duration ≥ 120 ms; QS or rS in lead V1; broad (frequently notched or slurred) R waves in leads I, aVL, V5,
or V6; and absent q waves in leads V5 and V6). The system requires thorough and precise measurements on the ECG tracings; it consists of 46-criteria from which a final score is obtained by adding up the number of points reached within each criteria group. A maximum of 32 points can be reached over eight investigated leads (I, II, aVL, aVF, V1, V2, V5, and V6).

Extracting the QRS measurements from a standard 12-lead ECG is a lengthy and tedious process. The quality of the scoring strongly depends on the familiarity of the reader with the method and the observers’ ability to consistently detect subtle QRS patterns such as notching and slurring. Therefore, we developed computer-based measurements of the Selvester score in LBBB patients to automatically deliver these measurements. The proposed software is called the ‘QUantitative and Automatic REport of Selvester Score (QuAReSS)'. In this work, we report its design and validation based on 216 ECGs selected from LBBB patients enrolled in the Multicenter Automatic Defibrillator Implantation Trial—CRT (MADIT-CRT). A total of 216 ECGs recorded prior to implantation were used from 216 patients with LBBB based on the new ‘strict’ LBBB criteria. For the learning set of ECGs, we randomly selected 36 ECGs from the pool of 216 ECGs. The expert ECG readers (B.W., D.S.) scored the 36 ECGs using the Selvester method. In case of discordant scoring, the ECGs were reviewed and discussed within a group of three experts (B.W., D.S., and G.W.). This dataset was used to set the detection and recognition rules of our software. Then, the remaining 180 ECGs were automatically processed using the QuAReSS software and the results were reviewed and adjudicated by one of the experts (B.W.). We evaluated the level of agreement between the fully automated results and the manually adjudicated ones.

Methods

The Selvester scoring method for LBBB patients is described in detail elsewhere. Currently, the proposed software automatically computes the final Selvester score by measuring 58 factors across eight leads (see Table 1) in addition to QRS duration (QRS onset and offset). Importantly, the software does not include an automatic evaluation of the strict definition of LBBB and therefore requires that the user ensures the presence of the strict LBBB to deliver valid scoring. In the following sections, we will describe the various methods we developed to automatically measure these factors.

Study population

This study involved the ECG recordings from patients enrolled in the Multicenter Automatic Defibrillator Implantation Trial—CRT (MADIT-CRT). A total of 216 ECGs were recorded prior to implantation were used from 216 patients with LBBB based on the new ‘strict’ LBBB criteria. For the learning set of ECGs, we randomly selected 36 ECGs from the pool of 216 ECGs. The expert ECG readers (B.W., D.S.) scored the 36 ECGs using the Selvester method. In case of discordant scoring, the ECGs were reviewed and discussed within a group of three experts (B.W., D.S., and G.W.). This dataset was used to set the detection and recognition rules of our software. Then, the remaining 180 ECGs were automatically processed using the QuAReSS software and the results were reviewed and adjudicated by one of the experts (B.W.). We evaluated the level of agreement between the fully automated results and the manually adjudicated ones.

ECG recordings

The 12-lead high-resolution ECGs were recorded before implantation using 24-h Holter recorders (H12+, Mortara Instrument, Milwaukee, WI, USA) with Mason-Likar lead configuration. The first 20-min ECG recordings were processed by the QuAReSS software and the results were reviewed and adjudicated by one of the experts (B.W.). We evaluated the level of agreement between the fully automated results and the manually adjudicated ones.

What’s new?

- A series of algorithms for automatically measuring the Selvester score in complete LBBB patients.
- A validation of the technology on data from the MADIT-CRT trial.
- A novel technology to expand the quantitative analysis of the surface ECG to the analysis of notches and slurs of the QRS signal.

Figure 1 Examples of ECG using strict LBBB definition and the QuAReSS software. Left panel: Illustration of the criteria for the strict LBBB definition in a male subject: QS or rS morphology in V1 (A), QRSd ≥ 140 ms for men or ≥ 130 ms for women (B), and mid-QRS notchting/slurring in at least two of the leads I, aVL, V1, V2, V5, and V6 (C). Right panel: the QuAReSS software provides a comprehensive user interface (UI) and visual guides to facilitate the manual adjudication of the automatic measurements required for the computation of the Selvester score. The upper part of the UI includes a set of tables encompassing all criteria of the Selvester score. The middle panel is a presentation of the standard 12-lead tracing, the right panel is the QRS signal currently reviewed that includes all detected patterns and interval measurements. The grey areas contain the QRS complex and the dark rectangle marks the first 40 ms of the QRS complex. Only the measurements required to compute the Selvester score are included in presentation of each QRS signal (lead aVF in this snapshot).
averaging technique relied on a synchronization method using a maximum likelihood estimation of the isoelectric line. The sampling frequency of the signal was 1000 Hz and amplitude resolution was 3.75 μV.

**Signal averaging**

The Holter recordings were originally annotated using commercial software (H-Scribe V4.0, Mortara Instrument) which provides the automatic detection of the QRS complexes. These annotations were reviewed and adjusted by an experienced technician. The baseline wander was estimated using linear fitting based on the isoelectric points located within the PR intervals to be subsequently subtracted from the signal. A QRS template based on 10 cardiac beats (correlation coefficient \( \geq 0.97 \)) was computed. The QRS signals highly correlated with the template (correlation coefficient equal to or \( > 0.95 \)) in \( \geq 6 \) leads were averaged. The averaging technique relied on a synchronization method using a maximization of the cross-correlation coefficient. The standard 12-lead ECG signals were constructed from the averaged signals using 8 × 8 conversion matrices developed by Man et al. 15

**Automatic scoring algorithms**

The method for automatically calculating the Selvester score includes: automatic positioning of the start and end of QRS complex, automatic characterization of the QRS morphology (the shape of QRS, such as QS or rS shape in lead V1), automatic localization of the wave peak and interval (the peak location of Q, R, and S waves, the beginning and end of Q and R waves), automatic detection of notches in the first 40 ms of the QRS and finally an automatic detection of mid-QRS notch/slur patterns. Following sections briefly describe the various methods and detection rules embedded in QuAReSS software developed for windows platform using Microsoft .NET framework 3.5.

**Table 1** List of 58 ECG measurements required for the computation of the Selvester score across the eight ECG leads

<table>
<thead>
<tr>
<th>Lead</th>
<th>I</th>
<th>II</th>
<th>aVL</th>
<th>aVF</th>
<th>V1</th>
<th>V2</th>
<th>V5</th>
<th>V6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q wave</td>
<td>7</td>
<td>0</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R wave</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S wave</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Notch</td>
<td>20</td>
<td>4</td>
<td>20</td>
<td>31</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R' wave</td>
<td>17</td>
<td>24</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S' wave</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>R mag.</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S mag.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Q mag.</td>
<td>18</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R mag.</td>
<td>4</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S mag.</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q dur.</td>
<td>15</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R dur.</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The numbers indicate the number of times that the indicated measurement was corrected in the manual scoring compared with the automated scoring.

**Detection of the QRS boundaries**

The accuracy of QRS boundaries is critical to the scoring system because QRS duration is one of the criteria for LBBB and the duration of Q and R (in leads V1 and V2) waves depends on the accurate definition of the beginning of the QRS complex. We implemented the detection of the QRS boundaries using the technique developed by Zong. 16 We made modifications to the algorithm to improve the location of boundaries for wider QRS duration usually recorded in LBBB patients, i.e. ranging from 130 to 200 ms. These adjustments include the elimination of the adaptive threshold procedure required for multiple beats signal, and an adjustment of the detection thresholds of the onset and offset of the complex to minimize the difference with the manual measurements from the learning set.

**Characterization of the QRS morphology**

To determine the QRS shape (one of the conditions for LBBB), we implemented a method identifying signal transitions (TR) and using the transition points (Tn) and their polarity to fit the following QRS classes: RS(+TR&-TR), QR(−TR+TR), R(+TR), and S(−TR) patterns (see example of RS pattern in Figure 2A). Only the transition point (Tn) surrounded on each side by a transition point (Tn − 1, Tn + 1) and associated with a magnitude changes > 10 μV (Hn > 10 μV and Hn + 1 > 10 μV), and spreading over >5 ms (Dn > 5 ms and Dn + 1 > 5 ms) is recorded as a ‘relevant QRS pattern’. To be registered as a transition (TR), the two last transition points (Tn and Tn + 1) of a ‘relevant QRS pattern’ must have opposite amplitude sign (signTn ≠ signTn + 1). The algorithm searches for Tn from the QRS onset to the QRS offset and QRS boundaries are considered transition points. Figure 2A provides an example of the detection of Tn for a schematic QRS complex with an RS configuration. Five transition points are shown in the figure while only two patterns are detected: R wave in T2 and S wave in T5.

**Q, R, and S waves locations and durations**

The scoring system depends on the measurements of the amplitude ratios and durations of Q, R, and S waves. For leads V1 and V2, the R wave is the first maxima of the QRS complex while in the remaining six leads the R wave definition differs from the standard clinical definition. Precisely, the R waves are located using a peak detection algorithm. First, we computed the first derivative of the QRS signal and applied a Gaussian filter. Then, the algorithm detects the sample(s) where the first derivative changes sign from positive to negative values (maxima). The maximum with the highest amplitude is labelled R (despite that it is not the first positive maxima of the QRS).

The searching for S wave is similar to R wave. The process starts from the detected R peak location or from one-third of QRS duration after QRS onset (if no positive inflection was found). The S wave position is defined as the most negative inflection of the QRS. The Q wave is defined as the first negative inflection of QRS complex. The search for Q wave begins at QRS onset and ends either at the R peak or before two-thirds of QRS duration (when no R wave is present). The detection method is the same as the one used for S wave and the decision rule is based on three criteria: (i) the absence of positive inflection before identifying the first negative inflection, (ii) Q wave height is \( > 0.02 \) mv in absolute value, and (iii) the Q wave width is \( > 5 \) ms.

The Selvester score criteria require the measurements of the durations of the Q and R waves in leads V1 and V2. The onset of the Q wave and R wave in leads V1 and V2 (with rS shape) is defined as the beginning of global QRS; the end is located where the signal returns to the isoelectric line.

There is no standard definition of QRS notch and slur patterns in modern quantitative electrocardiology. Therefore, we developed our own sets of criteria for notch and slur identification.
QRS notches

First, we limited our search for QRS notches inside a time interval delimited by QRS onset + 40 ms to QRS offset − 40 ms. Inside this intra-QRS signal, we search for a pattern of two contiguous transition points (positive to negative or negative to positive) associated with an angle > 90°. As shown in Figure 2B, we measured the duration and the amplitude of the changes, a notch requires an amplitude > 10 µV and a duration > 5 ms. Finally, notch patterns located < 20 ms from the R or S peak location are discarded since they would not be defined as R/R’ or S/S’ patterns.

QRS slurs

QRS slurs are subtle changes caused by the variation in the velocity of the ventricular activation wave front. Therefore, their detection is sensitive to signal noise. Our slur detection algorithm is built upon the detection of QRS notches, the angle between line fitting the segment prior each transition point (Tn) needs to form an angle superior to 90°, the duration and the amplitude of the notches should be > 10 µV and form a wave with a duration > 5 ms. (C) The slur detection relies on the first derivative (bold line) of the QRS wave (light line). The definition of a slur is based on the presence of a concave pattern and its presence is confirmed based on duration thresholds depending on the depth of the concave pattern.

Figure 2

Illustrations of the method designed to detect QRS pattern (A), QRS notching (B), and QRS slurring (C). See text for description of the method. (A) The transition points (Tn) of the QRS wave are detected based on amplitude and duration thresholds for each triplet of transition points (Tn − 1, Tn, and Tn + 1). Only the transition points that meet the criteria described below the panel are selected for fitting standard QRS morphology. (B) The detection of QRS notches, the angle between line fitting the segment prior each transition point (Tn) needs to form an angle superior to 90°, the duration and the amplitude of the notches should be > 10 µV and form a wave with a duration > 5 ms. (C) The slur detection relies on the first derivative (bold line) of the QRS wave (light line). The definition of a slur is based on the presence of a concave pattern and its presence is confirmed based on duration thresholds depending on the depth of the concave pattern.

The detections and measurements of the R/R’ (in leads V5–V6) and S/S’ (in leads V1–V2) start at the detected R and S wave, respectively. The automatic R/R’ detection is limited to an interval determined between the time point located 40 ms after QRS onset to the right boundary of R wave. If multiple peaks are detected, the tallest peak exceeding 0.01 mv is selected. The approach used for detecting S/S’ is similar to the one used for R/R’ and slur detection is applied only if no notch is detected.

Statistical analysis

The differences between automatic and adjudicated results were measured and quantified using Matlab (MATLAB2013b) and R software (R 3.02). The sensitivity and specificity were computed such as the sensitivity is the percentage of correctly identified patterns to the number of existing patterns, while the specificity is the percentage of true negative pattern. Mean and standard deviation values were reported for continuous measurements. The Bland–Altman plot was applied to estimate the difference and disagreement on Selvester scores between automatic and adjudicated scores.

Results

Table 1 lists the measurements across leads to compute the Selvester score. We investigated the number of discrepancies in score values following adjudication for each criterion of the Selvester score and across all leads, there are 46 criteria per ECGs to be assessed. Two hundred and four score points were manually adjusted amongst the 8280 scores (46 × 180) measured in the 180ECGs; therefore, 2.5% of the score have been adjudicated. As a note, the adjudication process may have led to change interval measurements or presence/
absence of pattern without changing the scoring; we observed that these were occurring very sparsely.

Comparing Selvester scores between automatic and manual method

The signal averaging process was applied to all ECG recordings. We obtained in average a noise level of 5.3 ± 11.7 μV over all ECGs. The lowest noise level was 3.4 ± 6.6 μV which was observed in lead aVL. The highest noise level was found in lead II (8.3 ± 11.8 μV). A total of 5400 measurements were made to calculate the Selvester score on the 180ECGs of the validation set. The average of absolute difference between automatic and adjudicated Selvester scores was 1.2 ± 1.5 points, and the paired difference was −0.4 ± 1.8 points. In average, the automatic score was lower than the adjudicated score. In Figure 3A, we report the Bland–Altman plot to illustrate the level of agreement between the scores with and without manual adjudication. There were 127 of 180 scores that were within one-point difference (3% infarct difference) and 152 scores were within two-point different range (Figure 3B). The largest difference was seven points (21% infarct). We investigated the sources of the discrepancies between the automatic and adjudicated scores by analysing the discrepancies between measurements.

QRS boundaries

The errors related to the locations of QRS onset, offset, and QRS duration did not play a significant role in the difference of the Selvester scores. The average difference in QRS onset between automatic and manually adjusted measurements was −1.4 ± 4.7 ms (earlier for automatic) while the location of QRS offset was −4.0 ± 5.0 ms earlier for the automatic results. Overall, the QRS duration was −2.6 ± 7.0 ms shorter compared with manually adjudicated results. These differences were too small to impact significantly the final scores.

Mis- and over-detected QRS patterns

The ability of the method to appropriately detect the Q, R, S, R′, and S′ waves are reported in Table 2 in terms of sensitivities and specificities. The sensitivity and specificity for Q, R, and S waves were 85%/100%, 100%/81%, and 99%/100%, respectively. The specificities for R′, S′, and NchInit40 were 92, 99, and 100%, and the sensitivities for these patterns were 76, 86, and 74%, respectively. Also, we measured the percentage of patterns that were either mis- or over-detected in automatic results across all measurements. The disagreements were 2.5, 1.3, and 1.3% for the Q, R, and S waves, respectively. Finally, 6.1 and 6.7% disagreements were observed for S′ and NchInit40. The highest disagreement was for R′ with 16.1%.

Intra-QRS interval measurements

The second component which impacted the Selvester score were the discrepancies in location and interval measurements. The Selvester scoring method associates specific number of points according to the durations of certain waves (Q and R) and amplitude ratios (R/Q, R/S, R/R′, and S/S′). We measured the differences in interval durations and the location of fiducial points before and after manual adjudication. Table 3 shows these results. Overall, the differences in wave durations, including Q and R duration, are within 5 ms range on average. Location differences for wave peak, wave onset, wave offset, and subtle patterns are under 2 ms except for R offset (the end of R wave) and S′ which are 3 and 5.7 ms, respectively.

Discussion

A frequent cause of chronic heart failure is the loss of contractile myocardium from MI. Infarct scar size is a major determinant of prognosis and closely related to the incidence of arrhythmias and sudden cardiac death. In addition, it may be important to identify the scar size and location when placing the LV pacing lead in CRT. Scar at or near the LV pacing site has been shown to have adverse effect on response to CRT. The standard 12-lead ECG-based Selvester scoring system is an easily accessible and inexpensive technique to evaluate the size of MI scar. Hence, automation of the Selvester system could deliver a strong clinical benefit and broad application to various challenges of modern electrophysiology.

Our automatic Selvester scoring system for LBBB was developed and trained from 36 ECGs and tested on 180 ECGs. With the large variability in conduction abnormalities in the heart-failure patients with LBBB of the MADIT-CRT cohort, we designed detection algorithms for the Q, R, and S waves and validated their performances. The QRS delineation was found to be sufficient quality. The challenge of this work pertained to the detection of QRS slurping and notching. Standard definitions for these QRS patterns do not exist, likely because definitions are difficult to apply manually by clinicians since they rely on very small amplitude and duration measurements. Still, our study demonstrates that these rules have nicely captured the
way our expert electrocardiographers defined these QRS patterns. Yet, our detection methods were not perfect. For instance, we report a 16% disagreement on detection of subtle pattern R prime. We examined the cases with disagreement and found a lack of accuracy in slur detection.

We linked these errors to the Selvester scoring by reporting in Table 1 the distribution of discrepancies associated with changes in scoring. The detection of the notch in lead V1, Q wave in lead V6 and lead I, and R’ and S’ in leads V5–V6 and V1–V2 have the strongest impact on the calculation of the Selvester score. These discrepancies represent more than half (n = 128) of the errors, furthermore missing these patterns (or adding them) is associated with errors in score using S’ amplitude and R wave duration (an additional 51 errors). Therefore, one would recommend to the user of the current version of the software to focus their manual adjudication on these specific patterns when using the QuAReSS software.

In this study, we developed a series of algorithms to automatically compute all the measurements and the 46 criteria required by the Selvester score in a few seconds. Importantly, the QuAReSS software provides a simple interface to review the measurements and to adjust them on the computer screen when needed. Our team of experts was able to review all measurements in a couple of minutes on average. Accessing a tool for a reliable and quick measurement of the Selvester score is expected to have significant clinical impact: (i) the technology could be used when cardiac imaging is not available in order to reduce noise of the signal. The use of 20-min ECG data is not available in the MADIT-CRT database. This step was implemented in toward the development of this additional feature.

Conclusion

We have developed an efficient method to enable automatic Selvester scoring of standard 12-lead ECGs with adjudication. Also the proposed algorithms can be easily modified to enable the computation of the Selvester scoring in patients with non-LBBB conduction before applying the QUARESS software to any ECGs. The automatic diagnosis of the presence of the strict LBBB is a challenging task due to the difficulty to discriminate between LV hypertrophy or slowed conduction in the myocardium.20 Our current efforts are directed toward the development of this additional feature.

We opted for using signal-averaged signals from 20-min recordings available in the MADIT-CRT database. This step was implemented in order to reduce noise of the signal. The use of 20-min ECG data is not a requirement for the computation of the Selvester score, i.e. a median beat from 10-s recording could be used as well. Yet, we did not evaluate the impact of using 10-s instead of 20-min-based average ECG with our method.

Limitations

One of the limitations of this study is a lack of an assessment of the inter-observer variability in the validation phase of the study. During the learning process, inconsistencies between observers were discussed in order to set specific rules and definition for QRS patterns. Therefore, this step was a learning process for the definition of the automatic algorithms but also for the observers. We did not check whether the design of these rules and definitions increased inter-observer variability on the learning set. One would expect that because of setting specific rules, the overall inter-observer variability should be lower. Importantly, the software does not include an automatic diagnosis of the presence strict LBBB.9 Therefore, the user of the software requires evaluating the presence of the strict LBBB

Table 2 Binary results of the presence or absence for waves and subtle patterns between automatic and adjudicate detections

<table>
<thead>
<tr>
<th>No. of measurement</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
<th>PPV (%)</th>
<th>NPV (%)</th>
<th>Disagreement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q wave</td>
<td>1080</td>
<td>85</td>
<td>100</td>
<td>96</td>
<td>98</td>
</tr>
<tr>
<td>R wave</td>
<td>1440</td>
<td>100</td>
<td>81</td>
<td>99</td>
<td>94</td>
</tr>
<tr>
<td>S wave</td>
<td>1440</td>
<td>99</td>
<td>100</td>
<td>100</td>
<td>96</td>
</tr>
<tr>
<td>R’ wave</td>
<td>360</td>
<td>76</td>
<td>92</td>
<td>91</td>
<td>79</td>
</tr>
<tr>
<td>S’ wave</td>
<td>360</td>
<td>86</td>
<td>99</td>
<td>98</td>
<td>92</td>
</tr>
<tr>
<td>Notch</td>
<td>360</td>
<td>74</td>
<td>100</td>
<td>94</td>
<td>93</td>
</tr>
</tbody>
</table>

Table 3 Continuous results between automatic and adjudicate measurements on wave duration and locations of wave peak, wave onset, wave offset, and subtle patterns

<table>
<thead>
<tr>
<th>Difference (ms) mean ± SD</th>
<th>No. of measurement</th>
<th>Number of ECG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q duration</td>
<td>1.9 ± 4.2</td>
<td>98</td>
</tr>
<tr>
<td>R duration</td>
<td>4.8 ± 19.9</td>
<td>285</td>
</tr>
<tr>
<td>Q peak</td>
<td>0.1 ± 1.0</td>
<td>120</td>
</tr>
<tr>
<td>Q onset</td>
<td>−1.7 ± 4.1</td>
<td>98</td>
</tr>
<tr>
<td>Q offset</td>
<td>0.2 ± 1.3</td>
<td>98</td>
</tr>
<tr>
<td>R peak</td>
<td>0 ± 11.2</td>
<td>1362</td>
</tr>
<tr>
<td>R onset</td>
<td>−1.8 ± 4.9</td>
<td>285</td>
</tr>
<tr>
<td>R offset</td>
<td>3.0 ± 19.5</td>
<td>285</td>
</tr>
<tr>
<td>R’</td>
<td>−1.8 ± 8.5</td>
<td>141</td>
</tr>
<tr>
<td>S peak</td>
<td>−0.2 ± 5.3</td>
<td>1013</td>
</tr>
<tr>
<td>S’</td>
<td>−5.7 ± 14.5</td>
<td>121</td>
</tr>
</tbody>
</table>
abnormalities or adapted to future potential updated versions of the Selvester QRS score.

Conflict of interest: The mention of commercial products, their sources, or their use in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products by the US Department of Health and Human Services.

References