Noninvasive electrocardiographic imaging assessment of conduction system pacing: A novel algorithm to assess intraventricular synchrony

Ivan Eltsov, MD,[1,2,3,*] Alvise Del Monte, MD,[1,*] Luigi Pannone, MD,[1] Ingrid Overeinder, MD,[1] Domenico Della Rocca, MD, PhD,[1] Roberto Scacciavillani, MD,[1] Frederik H. Verbrugge, MD, PhD,[4] Qingguo Zeng, PhD,[5] Gezim Bala, MD, PhD,[1] Andrea Maria Paparella, MSc,[1] Giacomo Talevi, MSc,[1] Erwin Stroker, MD, PhD,[1] Juan Sieira, MD, PhD,[1] Ali Gharaviri, PhD,[1] Andrea Sarkozy, MD, PhD,[1] Gian-Battista Chierchia, MD, PhD,[1] Mark La Meir, MD, PhD,[2,3] Carlo de Asmundis, MD, PhD,[1,†] Alexandre Almorad, MD[1,†]

From the [1]Heart Rhythm Management Centre, Postgraduate Program in Cardiac Electrophysiology and Pacing, Universitair Ziekenhuis Brussel - Vrije Universiteit Brussel, European Reference Networks Guard-Heart, Brussels, Belgium, [2]Cardiac Surgery Department, Universitair Ziekenhuis Brussel – Vrije Universiteit Brussel, Brussels, Belgium, [3]European Research Network GUARD-Heart, Brussels, Belgium, [4]Center for Cardiovascular Diseases, Universitair Ziekenhuis Brussel – Vrije Universiteit Brussel, Brussels, Belgium, and [5]Medtronic, Minneapolis, Minnesota.

BACKGROUND Left bundle branch area pacing (LBBAP) has become the procedure of choice for various indications including atrioventricular block and considered to be physiologic modality of pacing compared with right ventricular apex pacing.

OBJECTIVE The purpose of this study was to assess ventricular activation and synchrony in patients with an LBBAP device using electrocardiographic imaging (ECGI).

METHODS A total of 25 consecutive patients underwent an LBBAP device implantation were included in the study. Electrocardiography (ECG) and ECGI analyses have been performed the day after implantation. Native and paced QRS, left ventricular activation time, right ventricular activation time, and V1–V6 activation delay were calculated using ECG. Total ventricular activation time, left ventricular activation time, intrinsic left ventricular activation time, right ventricular activation time, intrinsic right ventricular activation time, and intraventricular dyssynchrony were calculated based on ECGI. All patients have been followed up to 12 months.

RESULTS All patients were divided in 2 groups (wide and narrow QRS) based on intrinsic ECG and then based on paced ECG parameters. The study showed that for initially narrow QRS group activation time and synchrony during pacing was comparable to native. In wide QRS group these parameters were significantly improved. For paced rhythm analysis classic ECG LBBAP parameters (paced QRS and left ventricular activation time) were not sufficient to properly evaluate the ventricular activation for paced rhythm. Discordance between classic ECG parameters and ECGI analysis was identified. Two additional 12-lead ECG parameters predicting the ECGI measurements were found. Follow-up did not show any worsening of ejection fraction, paced QRS, or pacing parameters.

CONCLUSION ECG imaging can bring a significant value into assessing the efficacy of new pacing modalities and provide much more data for precise determination of implantation outcome including detailed activation assessment and comparison with intrinsic conduction. Key ECGI values confirming proper ventricular activation have been defined, and corresponding 12-lead parameters were also identified, which allows to predict ventricular activation by using 12-lead ECG only.

KEYWORDS Left bundle branch area pacing; Electrocardiographic imaging; Intraventricular synchrony; Conduction system pacing; Noninvasive mapping; AV block; Heart failure; 3D mapping; Bradycardia

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*Drs Eltsov and Del Monte contributed equally to this work. †Drs de Asmundis and Almorad contributed equally to this work. **Address reprint requests and correspondence:** Dr Carlo de Asmundis, Heart Rhythm Management Centre, Postgraduate Program in Cardiac Electrophysiology and Pacing, Universitair Ziekenhuis Brussel – Vrije Universiteit Brussel, Laarbeeklaan 101, Brussels, Jette 1050, Belgium. E-mail address: carlo.deasmundis@uzbrussel.be.

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KEY FINDINGS

- Electrocardiographic imaging (ECGI) can bring significant value in the assessment of intraventricular synchrony after implantation of a left bundle branch area pacing device.
- A specific measurement technique has been developed to properly assess the intraventricular synchrony using ECGI.
- This method can be used to compare the synchrony between intrinsic and paced rhythm.
- Additional 12-lead electrocardiography parameters predicting ECGI measurements and therefore intraventricular synchrony were identified.

Introduction

In the last few years, the left bundle branch area pacing (LBBAP) technique has become the procedure of choice for patients with a structurally normal heart requiring permanent ventricular pacing (eg, atrioventricular block and persistent atrial fibrillation).[1] Conduction system pacing, especially His bundle pacing (HBP), avoids pacemaker (PM) syndrome and preserves the ejection fraction during permanent ventricular pacing. The most physiological pacing modality is HBP; however, the main advantage of LBBAP is that similar physiological ventricular pacing can be achieved with higher success rates.

Despite the huge interest in the LBBAP technique, published data remain scarce and definitions and distinctions between these modalities are not uniform, varying between different researchers.[2] Patients with a wide QRS complex could benefit from the improvement in the ejection fraction.[3] LBBAP shortens the QRS complex significantly compared with right ventricular (RV) pacing,[4] and full correction of a left bundle branch (LBB) block can more often and more easily be achieved compared with HBP.[2]

In the recent Multicenter European Left Bundle Branch Area Pacing Outcomes (MELOS) study, Jastrzębski and colleagues[5] concluded that LBBAP is a feasible technique to treat bradyarrhythmia; however, the success rate must be improved and clinical outcomes investigated in randomized trials.

The main keys to success in LBBAP implantation are the implantation site, intraventricular synchrony, and pacing parameters. Currently, the standard way to assess activation during and after LBBAP implantation is surface electrocardiography (ECG) and conduction system potentials. This requires not only solid ECG interpretation skills of the operator, but also often a second person at the recording system to analyze the activation. The same limitation may occur in the postprocedural follow-up.

Cheng and colleagues[6] recently showed that intraventricular synchrony can be achieved not only in pure LBB pacing groups, but also in other LBBAP modalities.

We hypothesized that noninvasive electrocardiographic imaging (ECGI) could be beneficial for intra- and postimplantation evaluation and optimization of LBBAP device therapy by precise visualization of ventricular activation and synchrony. This noninvasive high-fidelity technique allows the generation of activation maps and timings.[7] Other researchers have successfully used this technique for ventricular activation assessment after cardiac resynchronization therapy (CRT) device implantation, concluding that it provides reliable ventricular activation data and may be a useful adjunct to guide left ventricular (LV) lead implants and to perform postimplantation CRT optimization.[7,8] Another advantage of this technique is that it overcomes ECG interpretation issues, which may occur while dealing with patients with abnormal anatomy and/or suboptimal ECG patch placement.

Methods

Study design

This single-center prospective study included 25 patients who underwent LBBAP device implantation followed by ECGI evaluation. The study complies with the Declaration of Helsinki and was approved by the local ethics committees; informed consent was obtained from the subjects before inclusion in the study. All data were collected and updated in the registry of the Universitair Ziekenhuis Brussel and approved by the institutional ethics committee.

Study endpoints

The primary endpoint was the achievement of physiological pacing using the LBBAP technique described in European Heart Rhythm Association clinical consensus statement.[9] Other endpoints were ECGI assessment of intraventricular synchrony in different patient cohorts and evaluation of the differences between intrinsic and paced rhythms.

Patient population

Twenty-five consecutive patients who underwent LBBAP implantation were analyzed and included in the study. The inclusion criteria were a confirmed indication for ventricular pacing and stable lead position and parameters the day after implantation. Exclusion criteria were the presence of structural heart disease and severe heart failure requiring CRT.

LBBAP implantation procedure

Two different LBBAP implantation techniques were used: stylet-driven (Solia S60; Biotronik) and non–stylet-driven (SelectSecure 3830; Medtronic) lead implantation with a compatible sheath. Both techniques are well described in the literature[10–12]; the main procedural difference was that the use of leads with stylet allows the assessment of conduction system potentials and the morphology of paced QRS while screwing the lead into the ventricular septum.[10]

The main steps of the procedure can be summarized as follows: (1) transvenous access, (2) intraseptal placement of the pacing lead into the LV septal subendocardium in the LBB

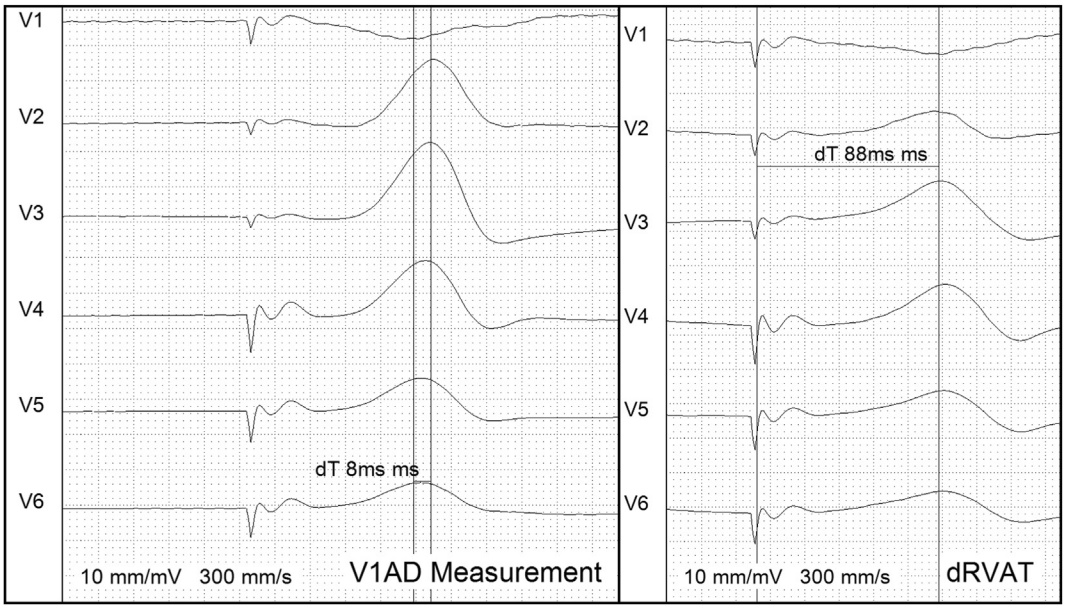

Figure 1 V1 activation delay (V1AD) and delayed right ventricle activation time (dRVAT) measurements on 12 Lead ECG. V1AD is measured from the absolute maximum peak in V6 to the absolute maximum peak of the R-wave in V1. dRVAT is measured from the pacing spike until the peak of R-wave in V1.

area, (3) confirmation of LBB capture, (4) placement of atrial connection leads in the PM, and (5) pocket closure. Procedures were performed either under general or local anesthesia. The day following implantation, the lead position was controlled via chest imaging, and complete device interrogation was performed to confirm stable PM parameters. LBB capture was confirmed by presence of screwing beat, morphology change during capture threshold testing, and ECG parameters.

Each implantation was assessed using standard 12-lead ECGs to measure classic LBBAP values: QRS, left ventricular activation time (LVAT) and right ventricular activation time (RVAT), and V1 activation delay (V1AD). All values were measured for intrinsic and paced rhythms. The measurement technique is illustrated on the Figure 1.

ECGI procedure

The ECGI procedure was performed 1 day after implantation, before discharge. A mapping vest (CardioInsight; Medtronic) was applied to the patient's chest and signal acquisition was initiated. Then, the PM configuration was modified to record intrinsic and unipolar paced rhythms and the corresponding bookmarks were created in the mapping system. Patients then underwent a chest computed tomography (CT) scan, which was segmented to align 272 surface electrodes with the epicardial shell (Figure 2).

Later, several activation and propagation maps were created using a signal averaging function to avoid false annotation due to noise. In our study, we performed single-beat mapping of the QRS complex for baseline (intrinsic) and paced rhythms.

Additionally, the LBBAP lead implantation site was identified during CT scan segmentation. Unsurprisingly its location perfectly matched the earliest activation site on all paced maps.

ECGI analysis

Several ventricular activation parameters of intrinsic conduction were measured: the ECGI total ventricular activation time (TVACT), the time interval between the first negative dv/dt of the earliest ventricular unipolar

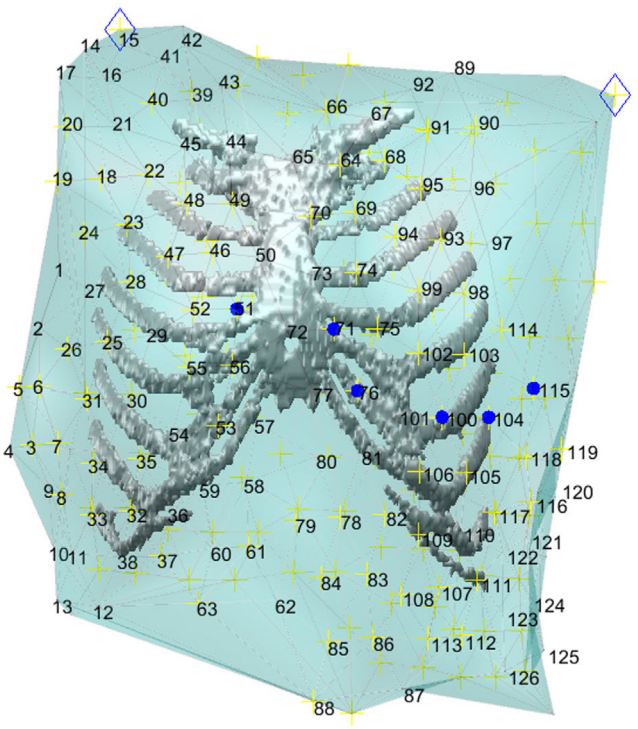

Figure 2 Electrocardiography and electrocardiographic imaging acquisition differences. Chest computed tomography scan with thoracic cage and vest electrode markers (yellow crosses). The blue dots are the reference positions of classic V leads.

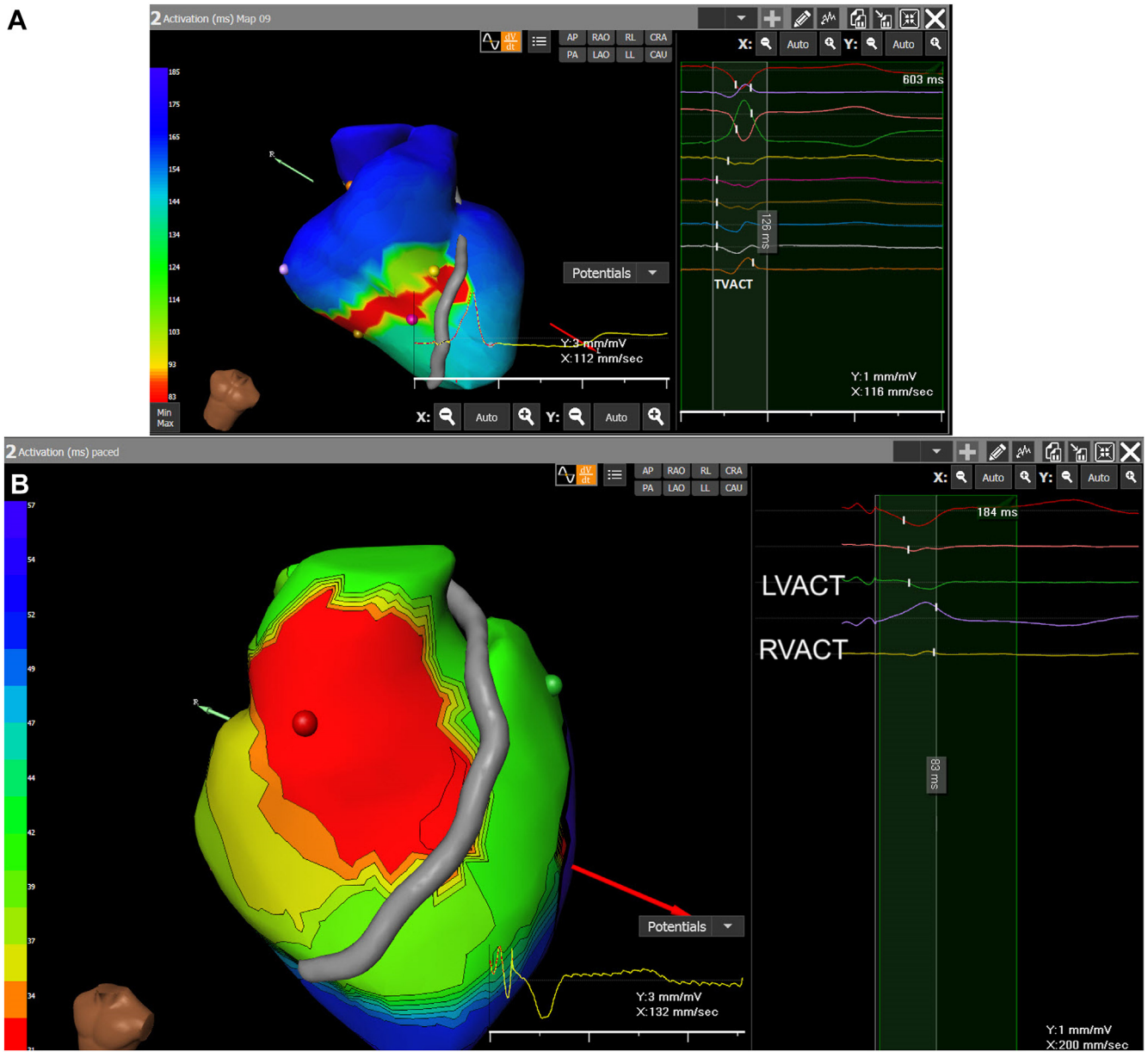

Figure 3 Electrocardiographic imaging total ventricular activation time (TVACT), electrocardiographic imaging left ventricular activation time (LVACT), and electrocardiographic imaging right ventricular activation time (RVACT) measurement on the electrocardiographic imaging total ventricular activation time activation map. A: TVACT measurements for paced rhythm—white caliper (126 ms) measuring from the first deflection of the earliest activation spot to the last deflection of the latest activation spot. B: LVACT and RVACT measurements for almost concomitant activation (the left ventricle activated slightly earlier). The white caliper measures the RVACT (83 ms) from the pacing spike to the steepest negative dv/dt at the latest RV activation point.

electrogram and the last dv/dt of the latest ventricular unipolar electrogram (Figure 3A); the ECGI LVAT (LVACT), the time interval between the pacing spike and the latest ventricular unipolar electrogram of the LV(Figure 3B); and the ECGI RVAT (RVACT), the time interval between the pacing spike and the latest ventricular unipolar electrogram on the RV (Figure 3B). A dynamic potential map was used to identify all the earliest and latest activation points on the map, and directional activation maps were used to measure time intervals. Intraventricular dyssynchrony (IVDS) was calculated as the difference between RVACT and LVACT.

Whether RVACT and LVACT values are ECGI equivalents of RVAT and LVAT, the TVACT value is slightly different. Due to a different measurement technique, the TVACT correlates well with paced QRS value, but it is normally slightly shorter.

For paced rhythm, the pacing spike was used as the starting measurement point for all intervals to ensure the consistency in comparing of ECG and ECGI timings.

Subsequently, both ECG and ECGI results were compared with identify potential discordance within different groups. TVACT values >130 ms were defined as a confirmation criterion of wide-paced QRS after LBBAP implantation.

Table 1 Patient characteristics

	Narrow QRS (n = 16)	Wide QRS (n = 9)	Overall (n = 25)	*P* value
Age, y	66.1 ± 16.5	73.7 ± 16.0	68.8 ± 16.5	.28
Male	7 (43.8)	9 (100)	16 (64.0)	.008
BMI, kg/m^2	30.0 ± 5.0	29.1 ± 5.0	29.7 ± 4.9	.64
Baseline ECG morphology				.003
LBBB morphology	7 (43.8)	2 (22.8)	9 (36.0)	
RBBB morphology	2 (12.5)	7 (77.8)	9 (36.0)	
Normal	7 (43.8)	0 (0.0)	7 (28.0)	
Preimplantation QRS duration, ms	95.1 ± 12.2	153.4 ± 16.9	112.9 ± 30.5	<.001
Ejection fraction, %	55.3 ± 5.0	53.9 ± 4.2	54.8 ± 4.7	.48
PR interval, ms	214.2 ± 76.7	191.2 ± 56.1	207.8 ± 70.8	.55
QTc interval, ms	434.2 ± 32.0	460.3 ± 41.8	443.6 ± 37.2	.09
SDL vs LLL	8/8	5/4	12/13	1.0
Sick sinus syndrome	13 (81.2)	5 (55.6)	18 (72.0)	.21
AV block	5 (31.2)	5 (55.6)	10 (40.0)	.39
Intraventricular conduction delay	0 (0.0)	1 (11.1)	1 (4.0)	.36

Values are mean ± SD, n (%), or n/n.

AV = atrioventricular; BMI = body mass index; LBBB = left bundle branch block; LLL = lumenless lead; RBBB = right bundle branch block; SDL = stylet-driven lead.

Every ECG-based value has an ECGI-based equivalent; LVAT and LVACT, delayed RVAT (dRVAT) and RVACT, and IVDS and V1AD. In addition, the difference between LV activation measured using 2 different techniques was analyzed. LBBAP pacing was considered "optimal" if the TVACT value was <130 ms and IVDS was positive or around zero.

All ECG measurements were also repeated for intrinsic and paced rhythm in all groups to identify clinical pacing outcomes.

Statistical analysis

The analysis was performed using R software version 3.6.2 (R Foundation for Statistical Computing).

All variables were tested for normality with the Shapiro-Wilk test. Normally distributed variables were described as mean ± SD and groups were compared through analysis of variance and paired or unpaired *t* test as appropriate. Non-normally distributed variables were described as median (interquartile range) and compared using the Mann-Whitney or Wilcoxon signed rank test, as appropriate. The categorical variables were described as frequency and percentage and compared by chi-square or Fisher's exact test, as appropriate. A *P* value <.05 was considered statistically significant.

Table 2 ECG measurements for LBBAP pacing

	pQRS <130 ms (n = 11)	pQRS ≥130 ms (n = 14)	Total (n = 25)	*P* value
pQRS, ms	117.5 ± 6.2	138.6 ± 9.5	129.3 ± 13.4	<.001
LVAT, ms	60.5 ± 8.6	77.1 ± 20.5	69.8 ± 18.2	.019
RVAT, ms	73.8 ± 20.2	98.0 ± 26.8	87.4 ± 26.6	.021
V1AD, ms	16.1 ± 17.3	20.2 ± 37.7	18.4 ± 30.0	.74

Values are mean ± SD.

ECG = electrocardiography; LBBAP = left bundle branch area pacing; LVAT = left ventricular activation time; pQRS = paced QRS; RVAT = right ventricular activation time; V1AD = V1 activation delay.

Results

Study population characteristics

Twenty-five consecutive patients who underwent LBBAP implantation met the inclusion criteria and were subjected to an ECGI procedure the day following implantation. All patients showed correct PM lead position via chest x-ray film and stable sensing and pacing parameters during device interrogation. Twelve (48%) procedures were performed using stylet-driven leads from Biotronik, and Medtronic lumenless leads were used in the remaining 13 (52%) patients. Based on a preprocedural 12-lead ECG, patients were divided into 2 groups: narrow QRS and wide QRS. Patient characteristics are summarized in Table 1.

At the end of the procedure, based on the ECG assessment, all patients were divided into 2 groups: paced QRS (pQRS) <130 ms and ≥130 ms. ECG measurements for the 2 pQRS groups are summarized in Table 2. The comparison of ECGI data between pQRS <130 ms and ≥130 ms is summarized in Table 3.

Table 3 Noninvasive ECGI analysis for pQRS groups

	pQRS <130 ms (n = 11)	pQRS ≥130 ms (n = 14)	Total (n = 25)	*P* value
TVACT, ms	111.5 ± 17.4	124.9 ± 17.0	119.0 ± 18.2	.04
LVACT, ms	76.0 ± 19.4	83.5 ± 30.8	80.2 ± 26.2	.001
RVACT, ms	82.5 ± 16.6	89.1 ± 21.1	86.2 ± 19.2	.41
IVDS, ms	0.2 ± 22.1	−4.8 ± 29.4	−2.6 ± 26.0	.03
LVADIF, ms	−16.8 ± 44.7	25.7 ± 59.0	7.0 ± 56.4	<.001
Confirmed, ms	9 (81.8)	7 (50.0)	16 (64.0)	.21

Values are mean ± SD or n (%).

ECGI = electrocardiographic imaging; IVDS = intraventricular dyssynchrony; LVACT = electrocardiographic imaging left ventricular activation time; LVADIF = left ventricular activation difference; pQRS = paced QRS; RVACT = electrocardiographic imaging right ventricular activation time; TVACT = electrocardiographic imaging total ventricular activation time; V1AD = V1 activation delay.

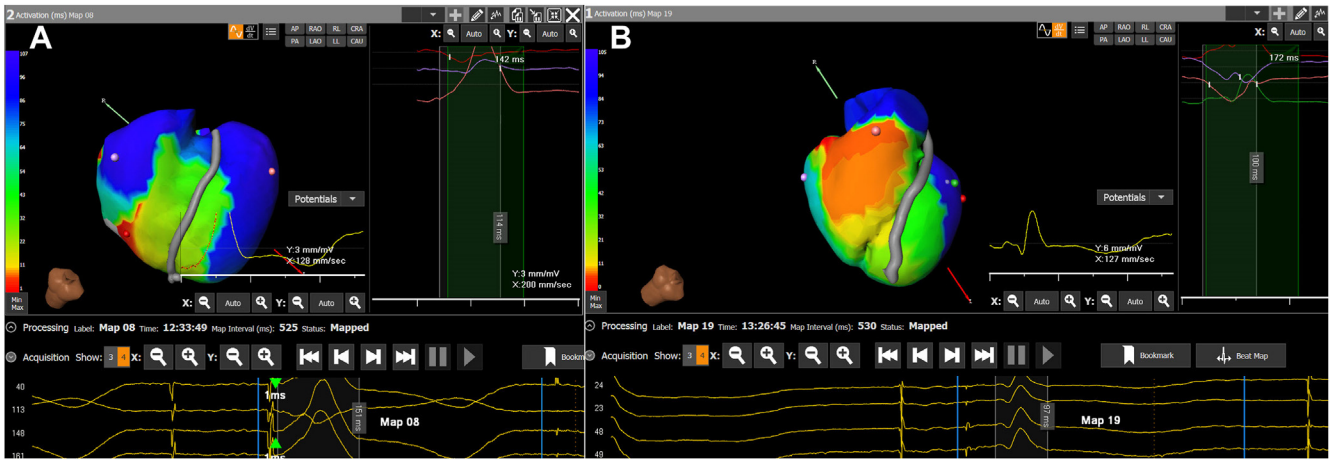

Figure 4 (Left)Concomitant activation of both ventricles in a wide paced QRS patient. (Right) "Right-first" activation of a patient with good classic left bundle branch area pacing electrocardiography measurements.

ECGI analysis confirmed only 7 pQRS ≥130 ms LBBAP as suboptimal (TVACT ≥130 ms). Two patients from the narrow pQRS group (pQRS <130 ms) had TVACT ≥130 ms.

The examples of concomitant ventricular activation in the wide pQRS group and "right-first" activation, despite good classic ECG values, are shown in Figure 4.

Analysis of the entire wide pQRS group showed that confirmed wide pQRS LBBAP is associated with higher TVACT and negative IVDS—both ECG and ECGI parameters are summarized in Table 4.

Based on the results shown in Table 4, 2 ECG values (V1AD and dRVAT) could predict TVACT and IVDS values. Figure 5 shows the workflow defined from these data, which identifies ECGI-guided physiological pacing based on ECG analysis alone.

Finally, we performed an ECG and ECGI analysis of the intrinsic rhythm in patients with baseline narrow vs wide QRS to compare the results achieved with LBBAP pacing (Table 5).

In the narrow QRS group, the results show that intrinsic and paced IVDS were not significantly different, signifying that LBBAP activated the ventricles in almost exactly the same way as the native conduction system (Figure 6).

However, in the wide QRS group, we found a significant improvement in intraventricular synchrony, and while the intrinsic rhythm was, as expected, not synchronous, the pQRS in this group was as good as in the narrow QRS group (Figure 7). This allowed us to conclude that, in the wide QRS group, the results of LBBAP were not different from the narrow QRS group based on pQRS and TVACT, RVACT, and IVDS. Twelve-month follow-up is summarized in the Table 6.

Discussion

Feasibility of activation visualization via ECGI

Several research groups have already demonstrated the possibility of using ECGI systems to visualize different paced rhythms (RV, CRT, LBBAP) and compare them visually with the intrinsic rhythm, even using these data to optimize pacing modalities (CRT).[6–8,13–15] Total activation time has been described by other investigators.[16,17]

In our study, in addition to visualization of activation during intrinsic and paced rhythms, activation times based on ECGI data were measured and compared with classic LBBAP assessment. We believe that the use of 252 electrodes around the torso during ECGI mapping allows us to

Table 4 ECGI vs 12-lead ECG parameters in non-confirmed wide pQRS patients

	Nonconfirmed by ECGI (n = 9)	Confirmed (n = 16)	Total (n = 25)	*P* value
pQRS, ms	135.1 ± 9.2	126.0 ± 14.5	129.3 ± 13.4	.1
V1AD, ms	17.3 ± 25.5	19.0 ± 33.1	18.4 ± 30.0	.9
dRVAT, ms	85.7 ± 24.4	88.3 ± 28.5	87.4 ± 26.6	.82
TVACT (ECGI), ms	115.2 ± 12.3	121.1 ± 20.9	119.0 ± 18.2	.45
IVDS (ECGI), ms	1.8 ± 27.9	−5.1 ± 25.6	−2.6 ± 26.0	.54

Values are mean ± SD.

dRVAT = delayd right ventricle activation time; ECG = electrocardiography; ECGI = electrocardiographic imaging; IVDS = intraventricular dyssynchrony; pQRS = paced QRS; TVACT = electrocardiographic imaging total ventricular activation time; V1AD = V1 activation delay.

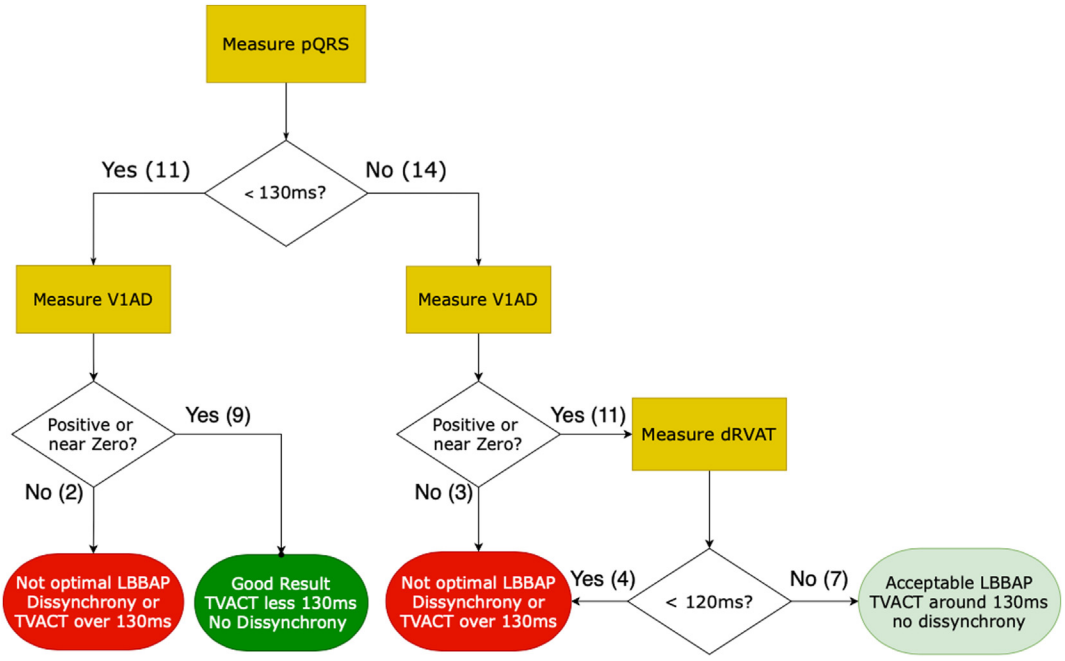

Figure 5 Suggested paced-rhythm electrocardiography analysis workflow. dRVAT = delayed right ventricle activation time; LBBAP = left bundle branch area pacing; pQRS = paced QRS; TVACT = electrocardiographic imaging total ventricular activation time; V1AD = V1 activation delay.

obtain much more detail of the activation. Together with CT scan details, it allows a better analysis of activation than classic 12-lead ECG, which can lead to missing some information due to anatomical differences and variable patch positioning.

True LBBAP confirmation

To achieve our primary endpoint, we analyzed the results of classic 12-lead ECG measurements and an ECGI study performed on the same day (1 day after device implantation). As ECGI measurements were conducted slightly differently (from spike to latest deflection) and because the ECGI system can visualize more data, as expected, the activation time values did not match entirely.

Individual activation times (LVACT and RVACT) mostly followed the trends of LVAT and RVAT with a difference of approximately 10 ms; however, the intraventricular synchrony measured classically and using ECGI presented greater discordance. We believe that this is related to the fact that classic 12-lead ECG cannot see the "leftmost" activation and is limited to the V6 electrode position. ECGI is projecting 360° of activation onto a precise 3-dimensional model, affording greater accuracy.[7,8]

In our study, we have used LVACT and RVACT values measured from spike until the last left or right deflection on ventricular activation and the difference between these values as a criterion for confirmation of "true LBBAP" implantation. The rationale for this is that LVAT and RVAT measured with ECGI were higher than those measured via ECG because

Table 5 Intrinsic vs paced ECG and ECGI measurements

	Narrow QRS (n = 16)	Wide QRS (n = 9)	Overall (n = 25)	*P* value
Preimplantation QRS duration, ms	95.1 ± 12.2	153.4 ± 16.9	112.9 ± 30.5	<.001
pQRS, ms	125.8 ± 13.0	135.6 ± 12.4	129.3 ± 13.4	.08
TVACT, ms	113.9 ± 17.5	128.0 ± 16.5	119.0 ± 18.2	.06
RVACT, ms	84.8 ± 22.6	88.8 ± 11.6	86.2 ± 19.2	.62
RVACTi	30.6 ± 21.6	78.8 ± 41.8	47.9 ± 37.8	<.001
LVACT, ms	74.5 ± 27.5	90.3 ± 21.4	80.2 ± 26.2	.15
LVACTi	34.1 ± 13.0	60.3 ± 30.4	43.5 ± 24.1	.006
IVDS, ms	−2.2 ± 24.4	−3.2 ± 30.3	−2.6 ± 26.0	.93
IVDSi	−3.5 ± 24.3	18.4 ± 68.0	4.4 ± 45.0	.25
IVDSDIF	−1.2 ± 40.2	21.7 ± 78.3	7.0 ± 56.4	.34

Values are mean ± SD.

ECG = electrocardiography; ECGI = electrocardiographic imaging; IVDS = intraventricular dyssynchrony; IVDSi = intrinsic intraventricular dyssynchrony; IVDSDIF = intraventricular dyssynchrony difference; LVACT = electrocardiographic imaging left ventricular activation time; LVACTi = electrocardiographic imaging intrinsic left ventricular activation time; pQRS = paced QRS; RVACT = electrocardiographic imaging right ventricular activation time; RVACTi = electrocardiographic imaging intrinsic right ventricular activation time; TVACT = electrocardiographic imaging total ventricular activation time.

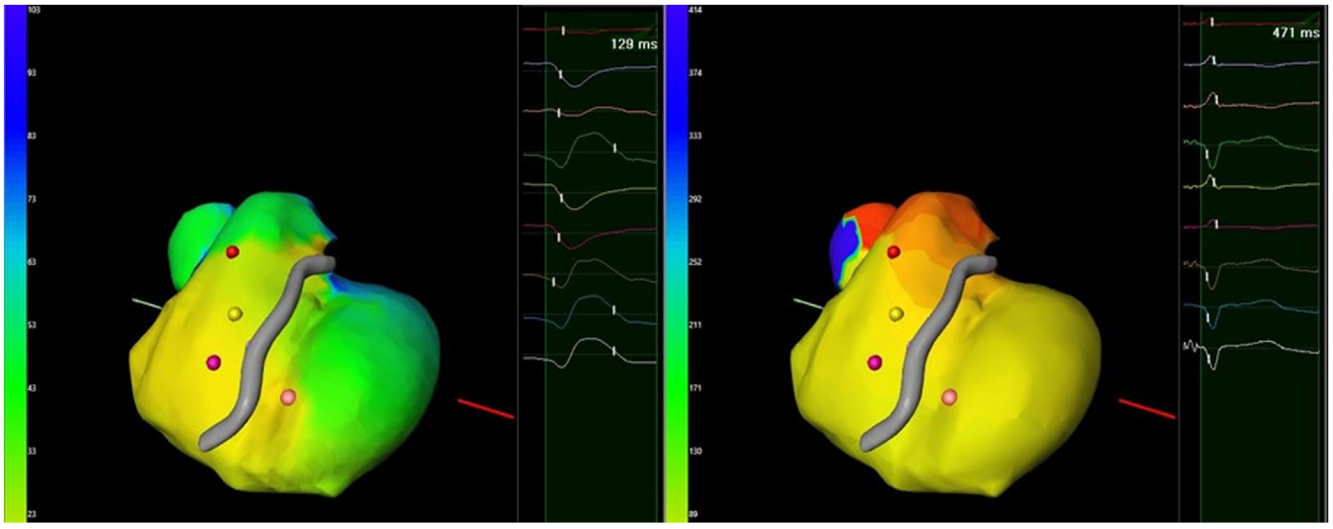

Figure 6 Activation maps of native and paced rhythms in patients with narrow intrinsic QRS.

instead of measuring up to the R-wave in V6 or V1, it measured until the last deflection.

We hypothesized that optimal LBBAP should be confirmed by 2 main ECGI parameters, TVACT and IVDS, as they most accurately reflect ventricular activation time and synchrony between the LV and RV. After analysis, we found that physiological activation correlated with TVACT <130 ms and positive IVDS (LV first) or around zero (concomitant activation).

With these parameters as control values, we reanalyzed our data and discovered that, in the short pQRS group, 2 patients did not have physiological ventricular activation despite good ECG parameters and, in the long pQRS group, 7 patients had good ventricular activation.

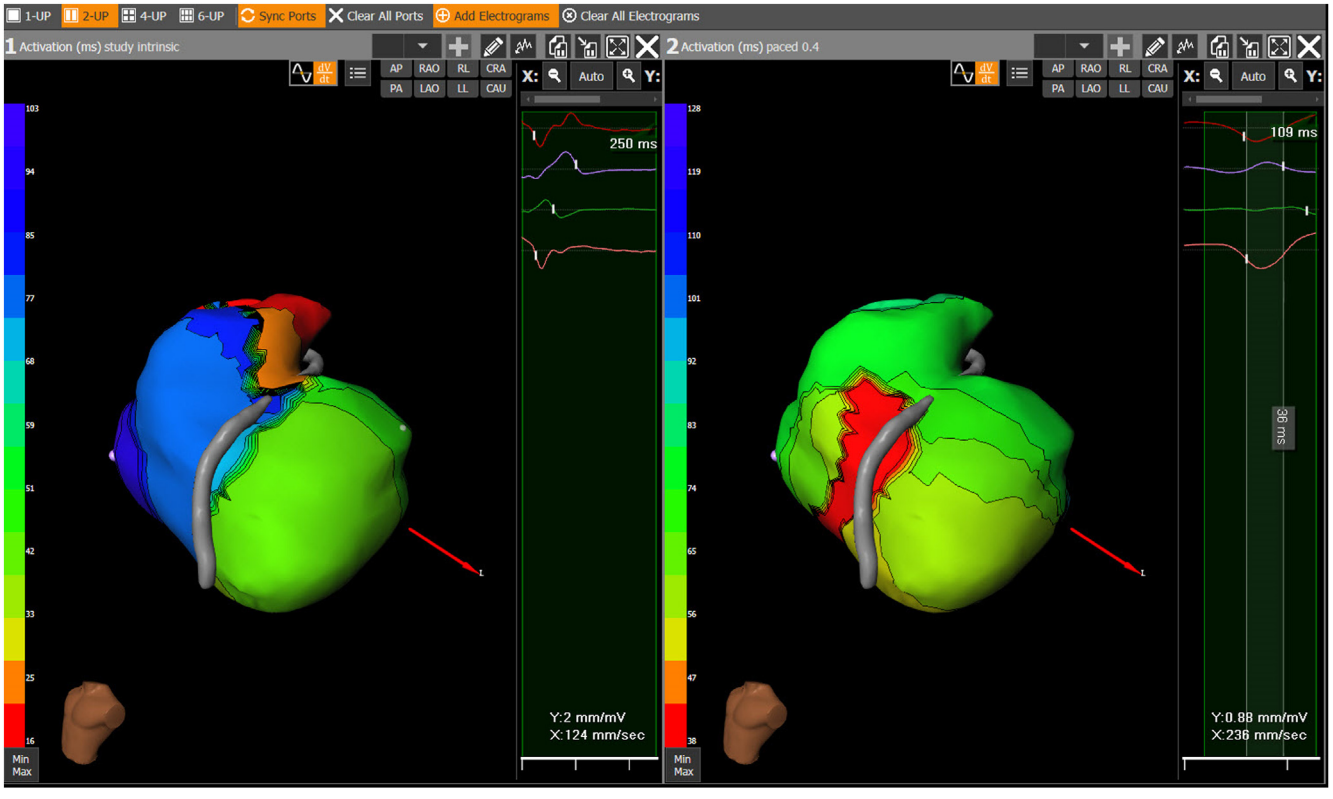

Figure 7 Improved ventricular activation in native wide QRS patients (right bundle branch block). (Left) Intrinsic activation map. (Right) Paced activation map. Red denotes the earliest activation point (pacing electrode).

Table 6 12-Month follow-up results: values POD and at 12 months

	POD 0 (n = 25)	12 mo (n = 25)	Total (n = 50)	*P* value
LVEF, %	54.8 ± 4.7	57.0 ± 4.6	55.9 ± 4.7	.099
Impedance, Ω	524.0 ± 103.5	493.3 ± 120.7	508.6 ± 112.3	.339
Threshold, V	0.6 ± 0.2	0.7 ± 0.4	0.7 ± 0.3	.078
Amplitude, mV	12.7 ± 3.7	12.2 ± 5.2	12.5 ± 4.4	.685

Values are mean ± SD.
LVEF = left ventricular ejection fraction; POD = postoperative day.

Even though ECGI provides an added value to LBBAP implantation assessment, the procedure is associated with increased radiation exposure (CT scan) and extra cost.[18]

Therefore, we performed a correlation analysis to determine which 12-lead ECG measurements could predict similar results.

Our analysis demonstrated that there were 2 ECG values (V1AD and dRVAT) that best correlate with our results and can theoretically predict TVACT and IVDS values.

As expected, V1AD is the best predictor of IVDS, as it measures the same process using different techniques. Thus, a negative V1AD is a discrimination factor, indicating that the RV activates first. In our study, this parameter qualified 5 patients (3 from the wide pQRS and 2 from the narrow pQRS groups) as suboptimal LBBAP (IVDS was also negative in all 5 patients).

Identifying a classic ECG parameter capable of predicting TVACT was less clear, as due to variations in anatomy and patch placement a narrow pQRS cannot be the only predictor of good TVACT. As demonstrated by our data (Figure 5 and Table 5), while there was a 100% correlation between pQRS and TVACT in the narrow pQRS group, the wide pQRS group exhibited some discrepancies. After a discrimination analysis, another 12-lead ECG parameter, dRVAT, could be used in addition to pQRS and V1AD to predict a good TVACT. Our study suggests that when dRVAT was >120 ms, it corresponded to a very long TVACT and suboptimal ventricular activation; however, if this parameter was <120 ms, the activation was close to physiological and might be accepted.

Intrinsic vs paced

Comparison with the intrinsic rhythm was also an important part of our research, as we could assess the physiological nature of the pacing in a particular patient in terms of intraventricular synchrony and bundle branch block correction (if present).

In our study, we categorized our patients into 2 groups—narrow and wide intrinsic QRS—and analyzed both intrinsic and paced rhythms using ECGI. The main criterion was IVDS, represented by the IVDS value (Table 5). Our study confirms that LBBAP can preserve ventricular activation times in patients with initially narrow QRS while significantly improving it in a native wide QRS cohort, in agreement with other investigators.[15,16]

Suggested implantation workflow

Based on our study, we recommend adding extra steps to intra- and postprocedural LBBAP confirmation by analyzing 2 extra parameters, V1AD and dRVAT, which can potentially help to identify physiological pacing without using ECGI. The suggested implantation workflow is summarized in Figure 5.

The long-term effect of intraventricular synchrony and IVDS after LBBAP device implantation needs to be assessed in future studies.

Limitations

This study reports a single-center experience. Furthermore, it is a nonrandomized trial conducted in a relatively limited number of patients. Heart failure patients were excluded from the study. There were no special echocardiographic protocols used to assess intraventricular synchrony.

Two patients from the narrow pQRS group were found to present significant ventricular dyssynchrony despite correct ECG parameters; they have been programmed for follow-up to confirm our findings, as this could potentially cause hemodynamic issues.

Conclusion

ECGI can bring significant value to assessing the efficacy of new pacing modalities and provide a greater amount of data for the precise determination of implantation outcomes, including detailed activation assessment and comparison with intrinsic conduction. Key ECGI values confirming proper ventricular activation were defined, and the corresponding 12-lead parameters were identified, which may help to predict ventricular synchrony using 12-lead ECG only during implantation. Further study is required to determine whether classical LBBAP implantation criteria and modality classification need to be updated based on this new information.

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Data Availability: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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