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Application of a new algorithm in the differential diagnosis of wide QRS complex tachycardia

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Brugada criteria;
Ventricular tachycardia;
Supraventricular tachycardia

Aims The Brugada criteria proposed to distinguish between regular, monomorphic wide QRS complex tachycardias (WCT) caused by supraventricular (SVT) and ventricular tachycardia (VT) have been reported to have a better sensitivity and specificity than the traditional criteria. By incorporating two new criteria, a new, simplified algorithm was devised and compared with the Brugada criteria.
Methods and results A total of 453 WCTs (331 VTs, 105 SVTs, 17 pre-excited tachycardias) from 287 consecutive patients with a proven electrophysiological (EP) diagnosis were prospectively analysed by two of the authors blinded to the EP diagnosis. The following criteria were analysed: (i) presence of AV dissociation; (ii) presence of an initial *R* wave in lead aVR; (iii) whether the morphology of the WCT correspond to bundle branch or fascicular block; (iv) estimation of initial (v_i) and terminal (v_t) ventricular activation velocity ratio (v_i/v_t) by measuring the voltage change on the ECG tracing during the initial 40 ms (v_i) and the terminal 40 ms (v_t) of the same bi- or multiphasic QRS complex. A $v_i/v_t > 1$ was suggestive of SVT and a $v_i/v_t \leq 1$ of VT. An initial *R* wave in lead aVR suggested VT. The overall test accuracy of the new algorithm was superior ($P = 0.006$) to that of the Brugada criteria. The new algorithm had a greater sensitivity ($P < 0.001$) and (−) predictive value (NPV) for VT diagnosis, and specificity ($P = 0.0471$) and (+) predictive value (PPV) for SVT diagnosis than those of the Brugada criteria [both NPV for VT diagnosis and PPV for SVT diagnosis were: 83.5% (95% confidence interval = CI 75.9–91.1%) for the new vs. 65.2% (95% CI 56.5–73.9%) for the Brugada algorithms].
Conclusion The new algorithm is a highly accurate tool for correctly diagnosing the cause of WCT ECGs.

Introduction

Wide QRS complex tachycardia (WCT) is a common arrhythmia with important therapeutic and prognostic implications and often presents a diagnostic challenge. WCTs may be ventricular in origin or may be supraventricular, conducted with fixed or functional bundle branch block (BBB) pattern, or supraventricular due to drug or electrolyte-induced changes or pre-excitation. Pre-excited tachycardias (PXT) and drug- and electrolyte-induced WCTs account for only a small minority (1–5%) of causes of WCT. Because most WCTs are either ventricular tachycardia (VT) or supraventricular tachycardia (SVT), conducted with fixed or functional BBB pattern, the clinically relevant problem in the differential diagnosis of WCTs is the differentiation of the latter two.[1] The ECG remains the cornerstone of distinguishing SVT from VT. A bewildering number of ECG criteria have been reported[2–17] for the differential diagnosis of regular WCTs. Using all these traditional ECG criteria, an accurate diagnosis is now possible in about 90% of WCTs.[2,3,10] However, many of these criteria are complicated and not consistently present, thus not useful in an urgent setting. Brugada *et al.*[7] proposed a relatively simple, stepwise, decision tree-like algorithm to differentiate between WCTs due to VT and SVT. However, that algorithm still retained the traditional morphological criteria in its last step. They reported that this algorithm had a sensitivity (98.7%) and specificity (96.5%) superior to those of the currently available criteria. Other authors[1,10,18] also found the Brugada criteria useful, though reported a lower sensitivity and specificity. Our aim was to devise another simplified, new algorithm for the differential diagnosis of WCTs by eliminating most of the complicated morphological criteria and compare it with the Brugada criteria.

Methods

A different set of patients was used to devise the algorithm from that used to test the already established algorithm. We used retrospectively 103 WCTs available in the database of Indiana University obtained from patients with proven electrophysiological (EP) diagnosis referred to EP study either because of spontaneous WCT or

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because of other clinical reasons and WCT was induced during the EP study. Then, to test the established algorithm, 453 regular WCT (331 VTs, 105 SVTs, 17 PXTs) tracings recorded from 287 consecutive patients during EP study conducted from June 1998 to November 2004 at Indiana University with proven EP diagnosis were prospectively analysed by two of the authors blinded to the EP diagnosis and the patients' clinical data. An informed consent exemption was obtained from the Indiana University Institutional Review Board for analysis of a deidentified dataset. The observers were given complete 12-lead standard ECGs obtained during tachycardia for analysis. WCT was defined as a rhythm with a rate $\geq$100 b.p.m. with a QRS duration $\geq$120 ms. Only monomorphic WCTs were analysed using the following criteria: (i) presence of A–V dissociation; (ii) presence of an initial *R* wave in lead aVR; (iii) whether the morphology of the WCT correspond to BBB or fascicular block [the diagnostic criteria proposed by Willems *et al*.[19] for intraventricular conduction disturbances were used (see *Table 1*)]; (iv) an index of slow conduction at the beginning and at the end of the QRS complex by estimation of initial (v_i) and terminal (v_t) ventricular activation velocity ratio (v_i/v_t), obtained by measuring the voltage in millivolts on the ECG tracing the impulse travelled vertically during the initial 40 ms (v_i) and the terminal 40 ms (v_t) of the same bi- or multiphasic QRS complex. The A–V dissociation criterion is identical in both algorithms (first criterion of the new and third of the Brugada algorithms). The v_i and v_t were measured in an individual QRS complex in any lead having a bi- or multiphasic QRS complex, in which the onset and end of the QRS were clearly visible and the initial ventricular activation was the most rapid (fastest). When either the initial or terminal 40 ms of the QRS complex displayed both positive and negative deflections, the sum of their absolute values (disregarding polarity) were used as the values of v_i and v_t. Because three channels were recorded simultaneously on the ECG tracings, the onset and end of the QRS were defined by the earliest and latest ventricular depolarization, respectively, among the three simultaneously recorded leads that included the lead with the fastest initial ventricular activation. Most frequently (in 87% of WCTs), the v_i was the fastest in the precordial leads and the leads most commonly used for analysis of v_i/v_t were v_3, v_5, and v_2 in decreasing order of frequency. Thus, limb leads were used to determine v_i/v_t in only 13% of WCTs. We hypothesized that a $v_i/v_t > 1$ was suggestive of SVT and a $v_i/v_t \leq 1$ of VT (*Figures 1* and *2*). The v_i/v_t criterion was validated in 111 ECG tracings recorded during sinus rhythm in patients with all types of intraventricular conduction disturbances, some of whom also had old myocardial infarction (MI). The v_i/v_t was >1 (signifying supraventricular origin) in 22/25 (88%) tracings with left BBB pattern, in 55/56 (98%) with right BBB pattern, and 27/30 (90%) with nonspecific intraventricular block pattern. The presence of an initial *R* wave (such as *R* or *RS* wave, but not *rS* wave) in lead aVR was hypothesized to suggest VT. The four criteria of the new algorithm were organized in a stepwise, decision-tree format similar to that of the Brugada algorithm (*Figure 3*). The four steps were used in the following sequence. (1) If A–V dissociation was present, the diagnosis of VT was made and the analysis was stopped. (2) If an initial *R* wave was present in lead aVR, the diagnosis of VT was made and the analysis was stopped. (3) If the morphology of WCT did not correspond to BBB or fascicular block, the diagnosis of VT was made and the analysis was stopped. (4) In the last step, when the v_i/v_t was ≤ 1, the diagnosis of VT was made, and if the v_i/v_t was >1, the diagnosis of SVT. Our algorithm, as well as the

Table 1 Criteria for the diagnosis of bundle branch and fascicular blocks

Definition of ventricular conduction delays	
A. Complete BBBs	B. Fascicular blocks
Qualifying statements S1) QRS duration $\geq$0.12 s (adults) S2) Supraventricular rhythm S3) Absence of WPW pattern Criteria for a complete BBB a) S1 and S2 and S3	
1. Complete right BBB (RBBB) Qualifying statements S1) *R′* or *r′* in V_1 or V_2 S2) *S* duration > *R* duration in I and V_6 S3) *S* duration >0.04 s in I and V_6 S4) *R* peak time >0.05 s in V_1 or V_2 Criteria for RBBB a) S1 and S2 or b) S1 and S3 or c) S4 and (S2 or S3)	1. Left anterior fascicular block (LAFB) Qualifying statements S1) QRS duration <0.12 s S2) QRS axis $\leq -30^\circ$ S3) *rS* pattern in II and III and aVF S4) *qR* pattern in aVL S5) *R* peak time $\geq$0.045 s in aVL S6) Slurred *R* downstroke in aVL S7) Slurred *S* in V_5 or V_6 Criteria for uncomplicated LAFB a) S1 and S2 and S3 and S4 and S5 or b) S1 and S2 and S3 and S4 and S6 or c) S1 and S2 and S3 and S4 and S7 Qualifying statement S3 is usually present with criteria a, b, and c above. If there is a QS in lead II, LAFB cannot be differentiated from inferior MI.
2. Complete left BBB (LBBB) Qualifying statements S1) Broad and notched or slurred R in I and V_5 or V_6 S2) Absence of *Q* wave in I and V_5 or V_6 S3) R peak times $\geq$0.06 s in V_5 or V_6 Criteria for LBBB a) S1 and S2 and S3	2. Left posterior fascicular block (LPFB) Qualifying statements S1) QRS duration <0.12 s S2) 180° > QRS axis >90° S3) qR pattern in III and aVF with Q duration $\leq$0.04 sec S4) Absence of other causes of right axis deviation Criteria for LPFB a) S1 and S2 and S3 and S4
3. Non-specific intraventricular block All cases with QRS duration >0.12 s which do not meet the criteria for LBBB or RBBB	

From Willems *et al*.[19] with modifications. Definitions for incomplete BBBs were omitted, because the QRS duration of the WCT tracings analysed in this study was $\geq$0.12 s.

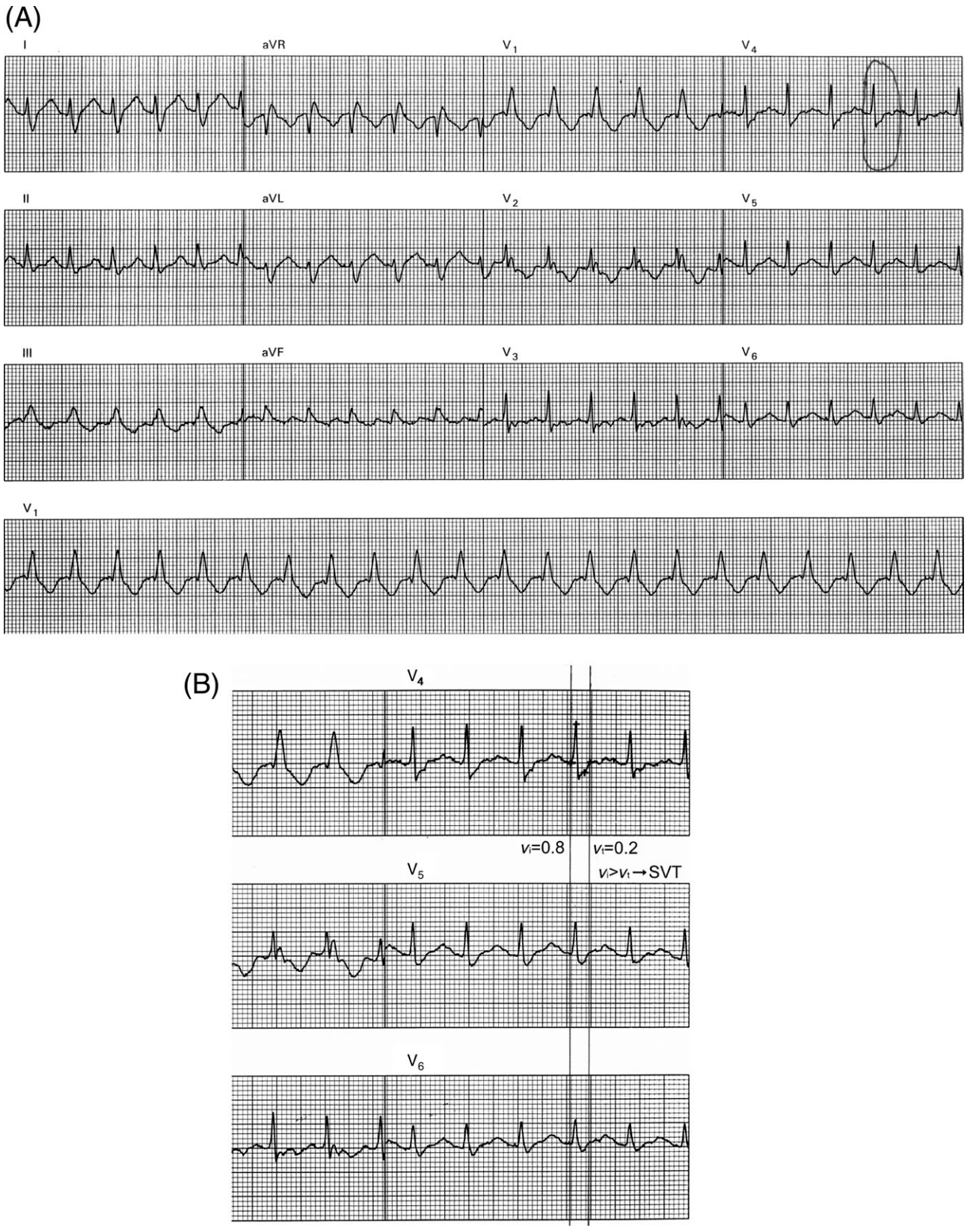

Figure 1 Application of the v_i/v_t criterion. *Figure 1A* shows a 12-lead WCT-ECG tracing. The v_i is measured in that lead where a bi- or multiphasic QRS complex is present and the initial ventricular activation is the fastest, and in that particular lead that QRS complex is chosen for the measurement of v_i and v_t where the onset and end of the QRS are clearly visible. In this example lead V_4 and within the lead, the encircled QRS complex meets the above requirements. *Figure 1B* shows a magnified view of leads V_{4-6} containing the encircled QRS complex in lead V_4 of the same ECG tracing shown in *Figure 1A*. Vertical lines are denoting the onset and end of the chosen QRS complex, the initial and terminal 40 ms of the chosen QRS complex is marked by small crosses. During the initial 40 ms of the QRS, the impulse travelled vertically 0.8 mV, therefore the $v_i = 0.8$ and during the terminal 40 ms of the QRS, the impulse travelled vertically 0.2 mV, therefore the $v_t = 0.2$, and thus the $v_i/v_t > 1$ suggesting the diagnosis of SVT.

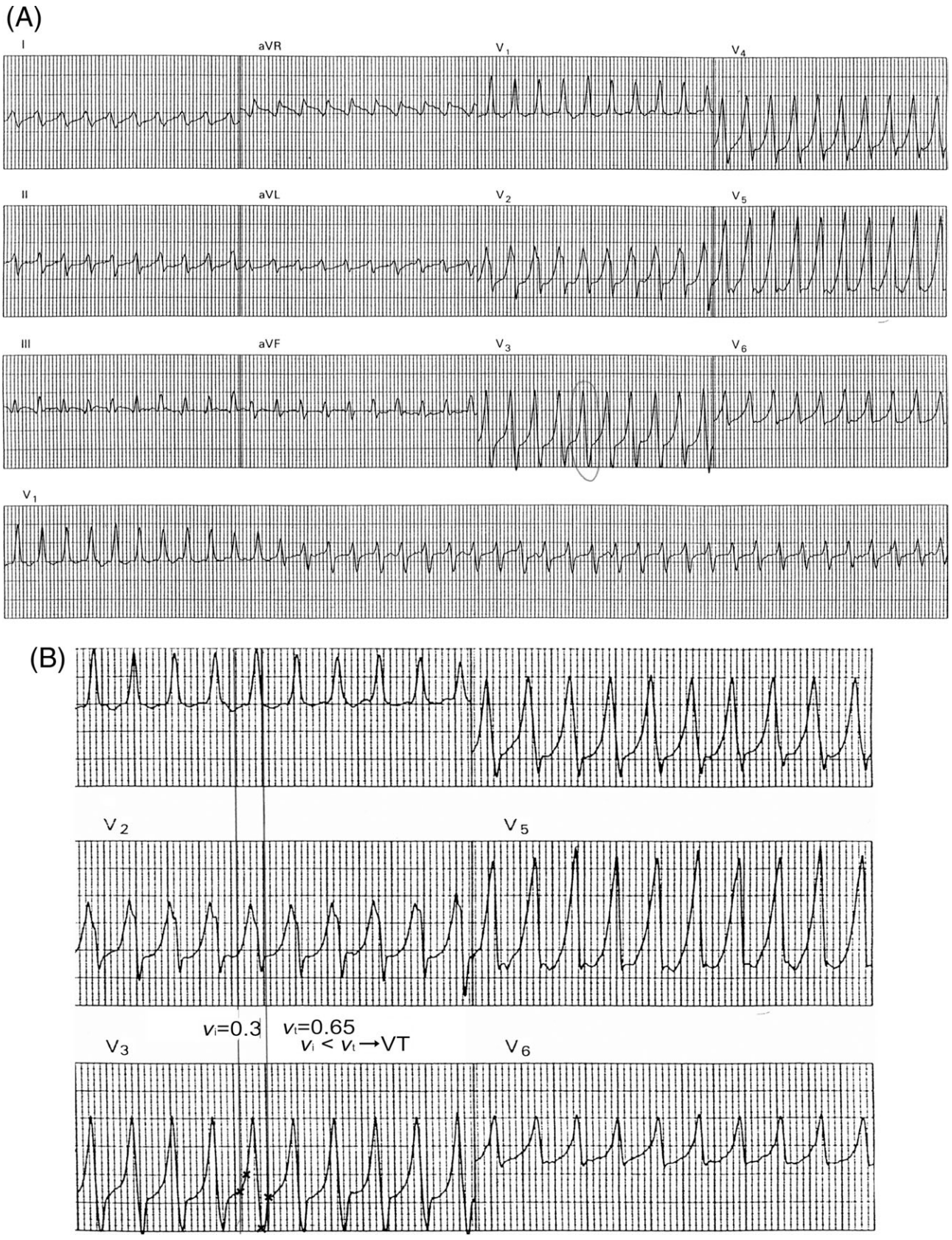

Figure 2 Application of the v_i/v_t criterion. *Figure 2A* shows a 12-lead WCT-ECG tracing. The QRS complex where the v_i and v_t are determined is chosen the same way as described in *Figure 1* and is encircled in lead V_3. *Figure 2B* shows a magnified view of leads V_{1-3} containing the encircled QRS complex in lead V_3 of the same ECG tracing shown in *Figure 2A*. The labels and measurement of v_i and v_t are the same as in *Figure 1B*. The $v_i = 0.3$ and $v_t = 0.65$ in this example, and thus the $v_i/v_t < 1$ suggesting the diagnosis of VT.

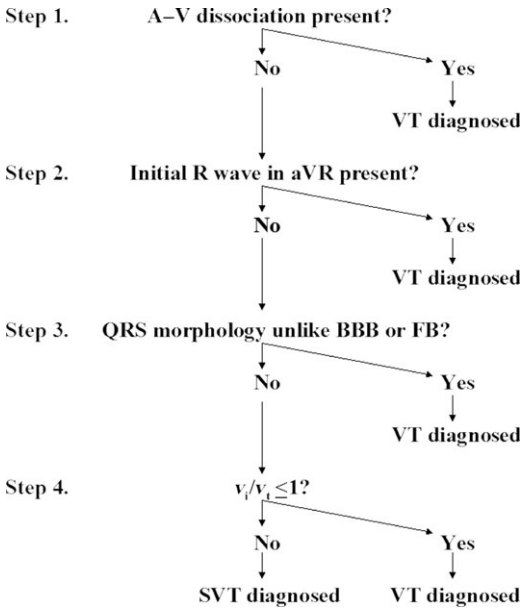

Figure 3 Brief summary of the new stepwise, decision-tree algorithm's use. FB, fascicular block.

traditional morphological ECG criteria, are unable to reliably differentiate VTs from PXTs in most WCT cases (with the exception of the presence of A–V dissociation and possibly that of an initial *R* wave in lead aVR along with other criteria suggested by Antunes *et al.*[9] that are infrequently present) and thus, the final diagnosis of VT in the third and fourth steps of the algorithm included also PXTs. *Figure 4* demonstrates an example how the new algorithm was applied.

Statistical analysis

Occurrence of true positive and negative, false positive and negative results expressed as percentage of the total number of observations as well as sensitivity and specificity were compared between two algorithms by first constructing 2×2 cross tables demonstrating where the two algorithms agreed or disagreed and then by using the non-parametric McNemar's test for comparing two related proportions, to determine which algorithm was better. The SPSS 13 for Windows software package (SPSS Inc., Chicago, IL, USA) was used for statistical analysis. A $P < 0.05$ value was considered statistically significant. However, the above described method was not suitable for the comparison of the predictive values, because in this case the denominators for the two algorithms differ (unlike specificity and sensitivity, where the denominators are the same). Lacking an entirely appropriate statistical method to compare the predictive values, these

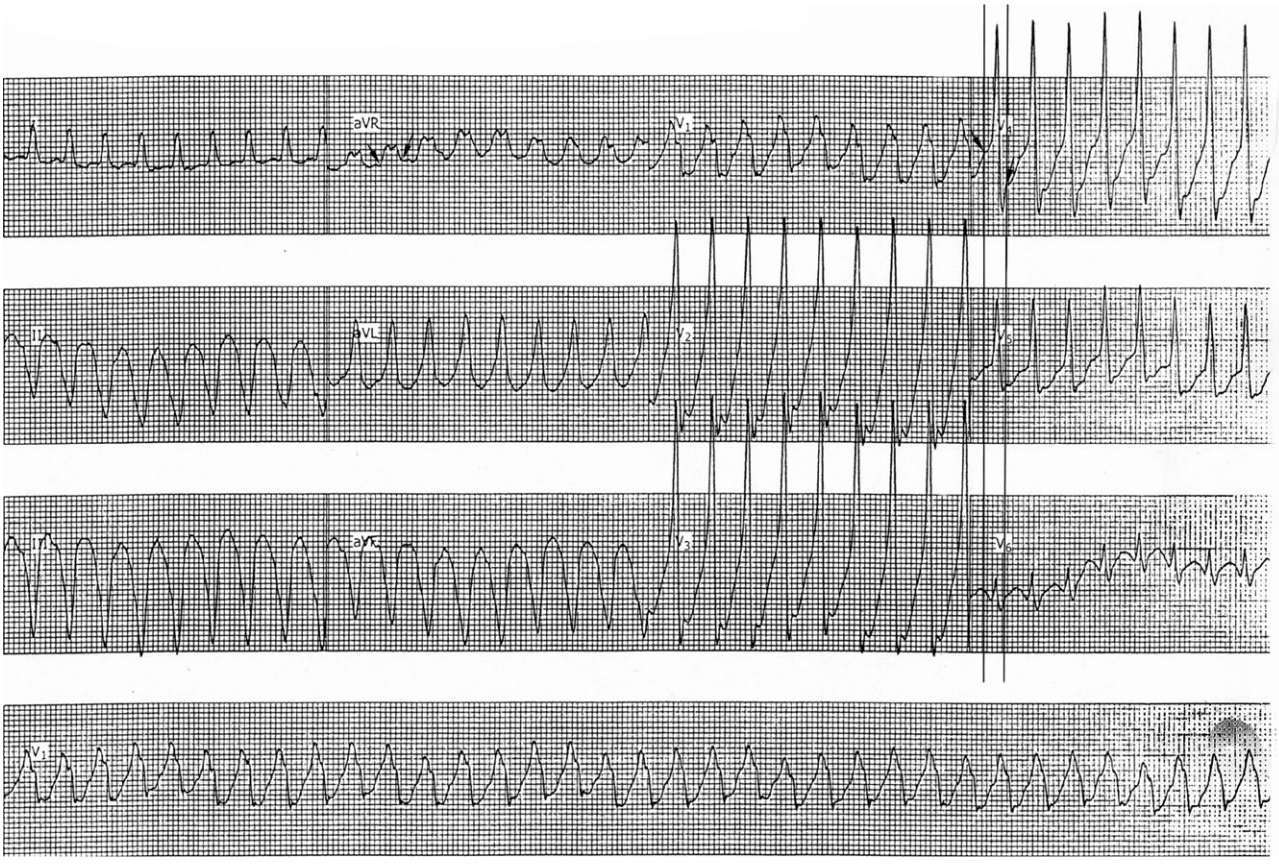

Figure 4 The application of the new algorithm. No A–V dissociation is present, therefore one must proceed to the next step of the algorithm. An initial *R* wave is present in lead aVR, thus, the final diagnosis is VT, and the analysis is stopped. This figure also demonstrates some of the difficulties met in the determination of QRS onset and end. A bi- or multiphasic QRS complex where the onset and end is discernible is seen only in leads V_4 and V_5 in this relatively fast VT/PXT. The onset is best seen in lead V_4 in the first QRS complex indicated by a sharp break (arrow) on the ST-T segment upslope of the previous QRS complex. The end of the QRS complex is again indicated by a sharp break before the start of its ST-T segment (arrow). The proper determination of the QRS onset and end can be confirmed by aligning them with the simultaneously recorded leads (V_5 and V_6) (see lines) where the lines also cross through breakpoints in the ECG contour compatible with the onset and end of the QRS. Another method to confirm the proper determination of QRS onset and end uses the fact that the QRS width should be the same in all leads. The QRS width that measures ~170 ms is clearly visible in the second QRS complex in lead aVR (arrows), similar to that of the first QRS complex in lead V_4 defined by the marked onset and end. The v_i/v_t calculated this way is ≤ 1 (0.075/0.75 measured in lead V_4) also supports the final VT diagnosis.

Table 2 Clinical characteristics

	SVT]$n = 105$	VT]$n = 331$	PXT]$n = 17$
Age (years) (mean ± SD)	45 ± 20	57 ± 17	36 ± 17
Female/male (%)	44/56	17/83	31/69
Antiarrhythmic drugs (%)	4	45	0
Pre-existent BBB(%)	25	35	0
Past history			
Post-MI (%)	4	61	0
Cardiomyopathy (%)	1	15	0
No structural heart disease (idiopathic) (%)	93	11	100

Table 3 The percentage of correct diagnoses (TA) made by different ECG criteria

Criterion	Correct diagnosis
All four criteria of the new algorithm	409/453 [90.3 (87.6–93)]
A–V dissociation = third Brugada	35/35 [100 (100–100)]
aVR (in all ECGs)	135/138 [97.8 (95.4–100.3)]
aVR (in the second step)	124/127 [97.6 (95–100.3)]
BBB, FB (in all ECGs)	273/293 [93.2 (90.3–96.1)]
BBB, FB (in the third step)	139/156 [89.1 (84.2–94)]
v_i/v_t (in all ECGs)	359/437 [82.2** (78.6–85.7)]
v_i/v_t (in the fourth step)	111/135 [82.2 (75.8–88.7)]
First Brugada	79/85 [92.9 (87.5–98.4)]
Second Brugada	195/212 [92.5 (88.3–95.6)]
Fourth Brugada	100/147 [68*** (60.5–75.6)]
All Brugada	384/453 [84.8* (81.5–88.1)]

The numbers represent the correct diagnoses/total number of tracings investigated with the criterion [percentage = TA (95% CI)]. The overall (both for VT and SVT diagnoses) TA of all four criteria of the new algorithm, all Brugada criteria and the v_i/v_t criterion applied to all ECGs were compared statistically. Also the overall TA of the v_i/v_t criterion applied in the fourth step was compared with that of the fourth Brugada criterion separately.

*$P < 0.01$, **$P < 0.001$ vs. all criteria of the new algorithm; ***$P < 0.01$ for the fourth Brugada criterion vs. the v_i/v_t criterion applied in the fourth step.

are presented simply with 95% confidence intervals (CI) without statistical comparison, and a significant between-groups difference in algorithms is indicated by disjoint (non-overlapping) CIs. Some patients are in the dataset more than once (several VTs with different morphology were induced in some patients while a few had WCTs due to both SVT and VT, occurred during the same EP study). Because these episodes behaved as independent, unrelated events, they were analysed as different WCT tracings in the study.

The Kappa statistic was used to quantify overall interobserver agreement using SAS statistical software package (SAS/STAT Software Release 6.12, SAS Institute Inc., Cary, NC, USA). Overall interobserver agreement was defined as good if $\kappa > 0.6$, moderate if $0.6 > \kappa > 0.4$, and poor if $\kappa < 0.4$.

Results

Patient characteristics

The patient groups differed in that the PXT and SVT groups had younger patients, more females, and fewer patients with a history of prior MI or cardiomyopathy and far more patients without structural heart disease than the VT group (*Table 2*). No patient in the PXT group and fewer patients in the SVT group took antiarrhythmic drugs or had pre-existent BBB than in the VT group.

Overall test accuracy

The new algorithm correctly classified 409 of 453 WCTs [90.3% (95% CI 87.6–93%) overall test accuracy (TA)] and was superior ($P = 0.006$) to that of Brugada algorithm [384/453 (84.8% overall TA) (95% CI 81.5–88.1%)] (*Table 3*). *Figure 5* shows a WCT misclassified by the Brugada criteria and classified correctly using the new algorithm. In the first step, the A–V dissociation criterion correctly diagnosed VT in 100%, in the second step, the aVR criterion in 97.6%, and in the third step, the BBB or fascicular block criterion in 89.1% of cases. In the fourth step, the v_i/v_t criterion correctly classified 111/135 [82.2% (95% CI 75.8–88.7%)] WCTs and was applicable in all cases. The diagnostic accuracy of each criterion was also evaluated individually in all WCT tracings. The TA of each criterion calculated in both ways was similar (*Table 3*). The TA of the first and second Brugada criteria were also good (>90%), however, that of the fourth Brugada criterion was significantly lower [68% (95% CI 60.5–75.6%) vs. 82.2% (95% CI 75.8–88.7%), $P = 0.004$] than the TA of the v_i/v_t criterion in the fourth step. Among all ECGs, the v_i/v_t criterion could not be applied in 16/453 (3.5%) cases, either because no bi- or multiphasic QRS complex was found in any of the 12 ECG leads or in some fast WCTs when the onset or end of the QRS complex could not be discerned. *Figures 4* and *6* demonstrate examples for difficulties in the determination of the QRS onset and end. The v_i/v_t criterion was thus applicable in 437/453 (96.5%) of WCTs; its overall TA was 359/437 [82.2% (95% CI 78.6–85.7%)], similar to that of the Brugada criteria [84.8% (95% CI 81.5–88.1%)] and inferior ($P < 0.001$) to a combination of all criteria of the new algorithm [90.3% (95% CI 87.6–93%)]. Interestingly, all 16 WCTs where the v_i/v_t criterion could not be applied were VTs. A total of 18 WCT episodes were misclassified by both the new and Brugada algorithms (*Figure 6*). The two observers produced very similar results: the interobserver variability was non-significant, as was the difference between the number of misclassified ECGs using both algorithms (results not shown). Therefore, only the results from observer 1 are published and used for analysis. *Figure 7* demonstrates the numbers of VT and SVT, true and false positive diagnoses made in each step of the new algorithm.

Sensitivity, specificity, and predictive values in VT diagnosis

Because only two final diagnoses (VT or SVT) were possible with the algorithms used, the specificity and positive predictive value (PPV) for VT diagnosis were the same as the sensitivity and negative predictive value (NPV) for SVT diagnosis (respectively), and inversely, the sensitivity and NPV for VT diagnosis were the same as the specificity and PPV for SVT diagnosis, respectively. The sensitivity [95.7% (95% CI 93.6–97.8%) vs. 88.2% (95% CI 84.8–91.6%), $P < 0.001$] and NPV [83.5% (95% CI 75.9–91.1%) vs. 65.3% (95% CI 56.7–73.8%)] for VT diagnosis of the new algorithm were superior to those of the Brugada criteria (*Table 4*). The

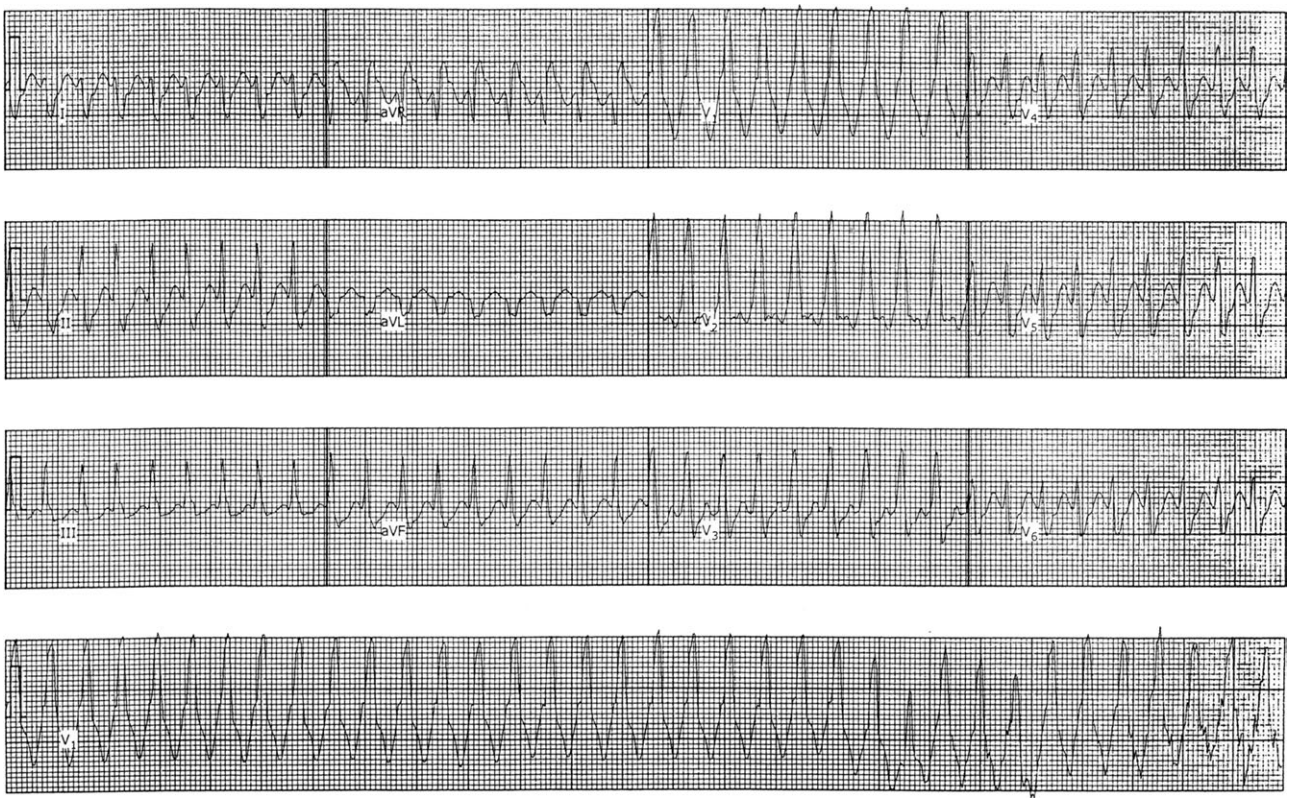

Figure 5 A WCT due to SVT that was classified correctly by the new algorithm and misdiagnosed by the Brugada criteria. RS complex is present, therefore the first Brugada criterion is not diagnostic, however, the longest R-to-S interval (second Brugada criterion) is >100 ms (RS = 110 ms in lead V_3) in the precordial leads, thus a final diagnosis of VT is made using the Brugada criteria. None of the first three criteria of the new algorithm suggest VT, the v_i/v_t is >1 (0.85/0.4 in lead V_5) suggesting SVT, thus the final diagnosis is SVT using the new algorithm.

specificity of the v_i/v_t criterion applied to all ECGs was greater for VT diagnosis than that of a combination of all criteria of the new algorithm and that of the Brugada algorithm [81.9% (95% CI 74.5–89.3%) vs. 72.4% (95% CI 63.8–80.9%) and 73.3% (95% CI 64.9–81.8%) respectively, $P = 0.004$ for the new and $P = 0.0173$ for the Brugada algorithm]. However, the sensitivity [95.7% (95% CI 93.6–97.8%) vs. 82.2% (95% CI 78.1–86.3%), $P < 0.001$] and NPV [83.5% (95% CI 75.9–91.1%) vs. 59.7% (95% CI 51.7–67.7%)] of the combination of all criteria of the new algorithm and the sensitivity of the Brugada algorithm [88.2% (95% CI 84.8–91.6%) vs. 82.2% (95% CI 78.1–86.3%), $P = 0.0277$] were superior to those of the v_i/v_t criterion alone applied to all ECGs. Among the other individual criteria, only the BBB, fascicular block criterion had a fairly high sensitivity (74.7%); all other individual criteria had relatively low sensitivity, despite their good specificity (*Table 4*). The aVR criterion was never positive in the 17 WCT episodes due to PXT, suggesting that it may be useful not only for distinguishing VT from SVT but also VT from PXT. The v_i/v_t criterion applied in the fourth step had a significantly greater sensitivity [70% (95% CI 57.3–82.7%) vs. 39.4% (95% CI 27.6–51.2%), $P < 0.001$] and NPV [83.5% (95%CI 75.9–91.1%) vs. 65.2% (95% CI 56.5–73.9%)] than the fourth Brugada criterion for VT diagnosis.

Sensitivity, specificity, and predictive values in SVT diagnosis

The specificity [95.7% (95% CI 93.6–97.8%) vs. 88.2% (95% CI 84.8–91.6%), $P = 0.0471$] and PPV [83.5% (95% CI 75.9–91.1%) vs. 65.3% (95% CI 56.7–73.8%)] for SVT diagnosis of the new algorithm were superior to those of the Brugada algorithm (*Table 4*). The specificity [95.7% (95% CI 93.6–97.8%) vs. 82.2% (95% CI 78.1–86.3%), $P < 0.01$] and PPV [83.5% (95% CI 75.9–91.1%) vs. 59.7% (95% CI 51.7–67.7%)] of the combination of all criteria of the new algorithm proved to be superior to those of the v_i/v_t criterion alone applied to all ECGs. The v_i/v_t criterion applied in the fourth step had a significantly greater specificity [70% (95% CI 57.3–82.7%) vs. 39.4% (95% CI 27.6% to 51,2%), $P < 0.001$] and PPV [83.5% (95% CI 75.9–91.1%) vs. 65.2% (95% CI 56.5–73.9%)] than the fourth Brugada criterion for SVT diagnosis.

Subgroup analysis

In the presence of pre-existent BBB, the overall TA of the new algorithm was superior [(92.2% (95% CI 87.8–96.6%) vs. 85.8% (95% CI 80.1–91.6%), $P = 0.027$] and in the presence of idiopathic VT was borderline superior [(86.5% (95% CI 75.5–97.5%) vs. 67.6% (95% CI 52.5–82.7%), $P = 0.065$] to that of the Brugada algorithm (*Table 5*). When both pre-existent BBB and class I antiarrhythmic drug or amiodarone treatment were present, the overall TA of the new algorithm was borderline superior [97.6% (95% CI 94.4–100.9%) vs. 92.9% (95% CI 87.3–98.4%), $P = 0.063$] to that of the Brugada criteria. For VT diagnosis, the new algorithm had a significantly better sensitivity [100% (95% CI 100–100%) vs. 95.9% (95% CI 92.7–99.1%), $P = 0.031$] and NPV [100% (95% CI 100–100%) vs. 33.3% (95% CI 2.5–64.1%)] in the

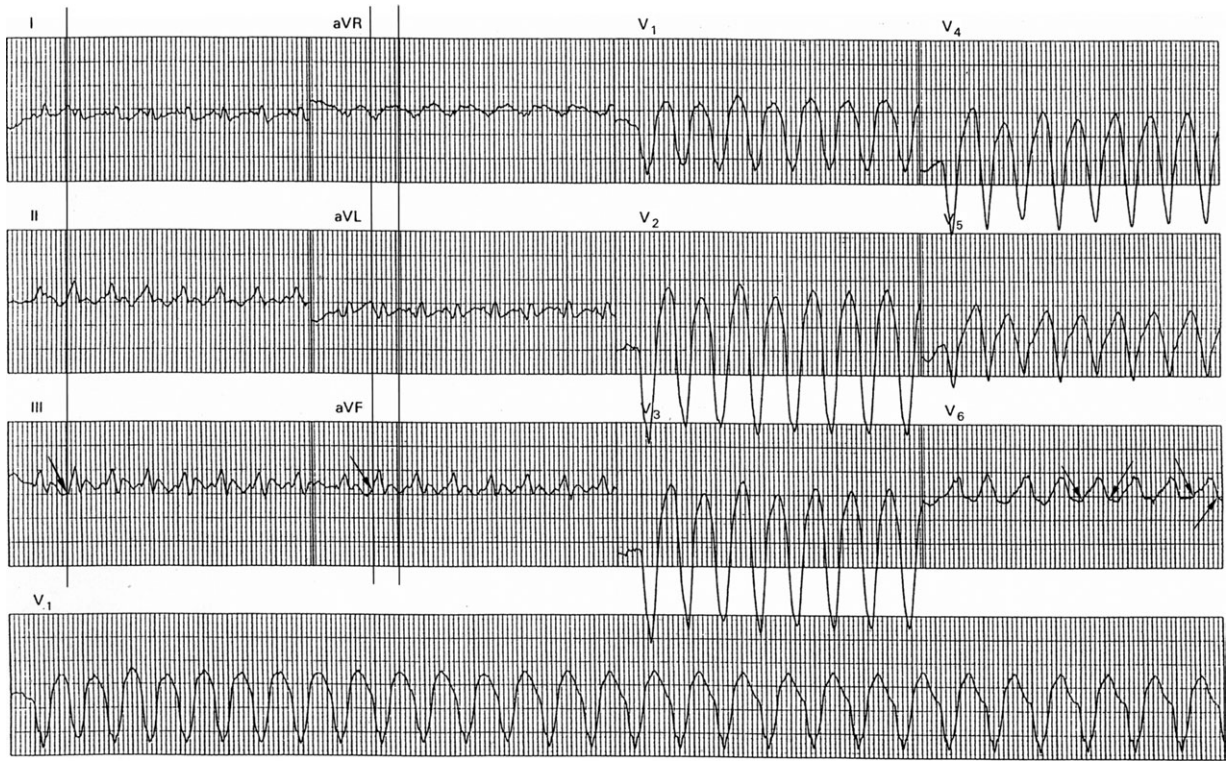

Figure 6 A WCT due to SVT that was misdiagnosed by both the new and the Brugada algorithms. The RS complex is absent in the precordial leads, therefore the first Brugada criterion suggests VT. Using the new algorithm, there is no A–V dissociation and no initial *R* wave in aVR, the QRS morphology not consistent with any BBB or fascicular block pattern (in lead I there is an *RS* wave not consistent with left BBB pattern), thus the final diagnosis is VT. Interestingly the v_i/v_t is >1 (0.3/0.2 in lead aVF) suggesting the correct diagnosis of SVT. In this tracing, no bi- or multiphasic QRS complex is seen in the precordial leads, thus the v_i/v_t should be estimated in the limb leads where it is quite difficult to find the QRS onset and end. The QRS width can be estimated in the fifth and eighth QRS complexes in lead V_6 as ~220 ms (arrows). The QRS onset is indicated by the sharpest breakpoints in the QRST contour best seen in leads III and aVF (marked by arrows and the crossing points with lines), confirmed by aligning these breakpoints with those of the simultaneously recorded leads (see first and second lines from the left side). The greatest v_i is seen in the second complex in lead aVF. Measuring the estimated QRS width of 220 ms from the onset of this QRS, we arrive to another sharp breakpoint (marked by the third line from the left side) that corresponds to the end of the QRS complex.

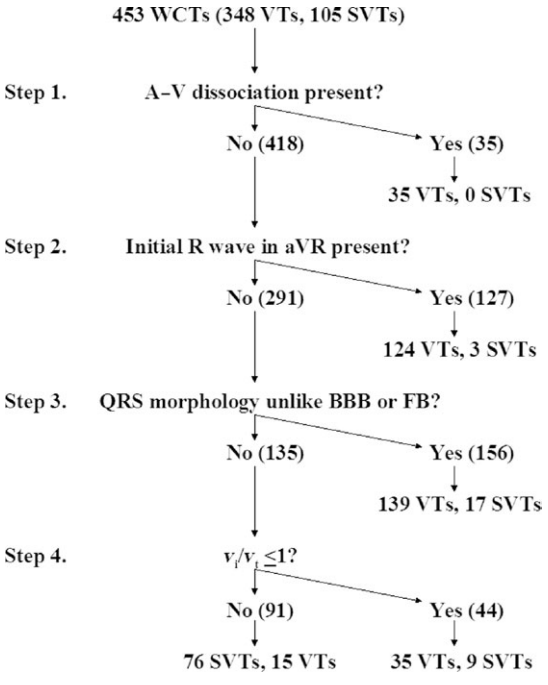

Figure 7 Numbers of VT and SVT, true and false positive diagnoses made in each step of the new algorithm. FB, fascicular block.

presence of class I antiarrhythmic drug or amiodarone treatment, and in the presence of pre-existent BBB, a borderline superior sensitivity [98.3% (95%CI 95.9–100.7%) vs. 92.2% (95% CI 87.3–97.1%), $P = 0.065$], and a borderline superior NPV [89.5% (95% CI 75.7–103.3%) vs. 62.5% (95% CI 43.1–81.9%)] compared with the Brugada criteria. The sensitivity of the new criteria in diagnosing VT in the case of idiopathic VTs was borderline superior [86.5% (95% CI 75.5–97.5%) vs. 67.6% (95% CI 52.5–82.7%), $P = 0.065$] to that of the Brugada criteria. The PPV for SVT diagnosis of the new criteria was borderline superior [89.5% (95% CI 75.7–103.3%) vs. 62.5% (95% CI 43.1–81.9%)] to that of the Brugada criteria in the presence of pre-existent BBB.

Discussion

Major findings

Our new algorithm for the differential diagnosis of WCTs has been shown to have a significantly better overall TA: a greater sensitivity and NPV in VT diagnosis and a greater PPV and specificity in SVT diagnosis compared with the Brugada criteria. The overall TA of our relatively simple new algorithm, which eliminated most of the difficult-to-recall morphological criteria, was on a par with the use of all published traditional ECG criteria.[3,10]

Table 4 The sensitivity, specificity and predictive values of different ECG criteria for the differential diagnosis of WCT

Criterion	Sensitivity		Specificity		(+) Predictive value		(−) Predictive value	
	VT Dx	SVT Dx	VT Dx	SVT Dx	VT Dx	SVT Dx	VT Dx	SVT Dx
All new algorithm criteria	**95.7** *(93.6–97.8)*	**72.4** *(63.8–80.9)*	**72.4** *(63.8–80.9)*	**95.7** *(93.6–97.8)*	**92** *(89.2–94.8)*	**83.5** *(75.9–91.1)*	**83.5** *(75.9–91.1)*	**92** *(89.2–94.8)*
A–V dissociation	**10.1** *(6.9–13.2)*		**100** *(100–100)*		**100** *(100–100)*		**25.1** *(21–29.3)*	
aVR (in the second step)	**39.6** *(34.2–45)*		**97.1** *(94–100.3)*		**97.6** *(95–100.3)*		**35.1** *(29.6–40.5)*	
BBB, FB (in the third step)	**74.7** *(68.5–81)*		**83.3** *(76.1–90.6)*		**89.1** *(84.2–94)*		**64.4** *(56.2–72.6)*	
v_i/v_t (in the 4th step)	**70** *(57.3–82.7)*	**89.4** *(82.9–96)*	**89.4** *(82.9–96)*	**70** *(57.3–82.7)*	**79.5** *(67.6–91.5)*	**83.5** *(75.9–91.1)*	**83.5** *(75.9–91.1)*	**79.5** *(67.6–91.5)*
v_i/v_t (in all ECGs)	**82.2***,† *(78.1–86.3)*	**81.9**† *(74.5–89.3)*	**81.9****,† *(74.5–89.3)*	**82.2**** *(78.1–86.3)*	**93.2** *(90.3–96.1)*	**59.7**^{a} *(51.7–67.7)*	**59.7**^{a} *(51.7–67.7)*	**93.2** *(90.3–96.1)*
First Brugada	**22.8** *(18.4–27.2)*		**94.3** *(89.9–98.7)*		**92.9** *(87.5–98.4)*		**27.2** *(22.6–31.7)*	
Second Brugada	**56.5** *(51.3–61.7)*		**84.9** *(78.1–91.7)*		**92.5** *(88.9–96)*		**37.3** *(31.2–43.5)*	
Fourth Brugada	**39.4**$^{\delta\delta\delta}$ *(27.6–51.2)*	**91.5** *(85.4–97.5)*	**91.5** *(85.4–97.5)*	**39.4**$^{\delta\delta\delta}$ *(27.6–51.2)*	**78.8** *(64.8–92.7)*	**65.2**^{b} *(56.5–73.9)*	**65.2**^{b} *(56.5–73.9)*	**78.8** *(64.8–92.7)*
All Brugada	**88.2*** *(84.8–91.6)*	**73.3** *(64.9–81.8)*	**73.3** *(64.9–81.8)*	**88.2***** *(84.8–91.6)*	**91.6** *(88.7–94.6)*	**65.3**^{a} *(56.7–73.8)*	**65.3**^{a} *(56.7–73.8)*	**91.6** *(88.7–94.6)*

Dx, diagnosis. Bold numbers represent percentage values; italic numbers in parentheses are 95% CI. The sensitivity, specificity, and predictive values of all four criteria of the new algorithm, all Brugada criteria, and the v_i/v_t criterion applied to all ECGs were compared statistically and those of the v_i/v_t criterion applied in the fourth step were also compared with those of the fourth Brugada criterion separately. A significant between-groups difference in predictive values ([a]vs. all criteria of the new algorithm, [b]fourth Brugada criterion vs. the v_i/v_t criterion applied in the fourth step) is indicated only by disjoint (non-overlapping) 95% CI. For sensitivity and specificity: $^{*}P < 0.001$, $^{**}P < 0.01$, $^{***}P < 0.05$, vs. all criteria of the new algorithm, [†]significant. ($^{\dagger}P < 0.05$, $^{\dagger\dagger}P < 0.01$, $^{\dagger\dagger\dagger}P < 0.001$) difference between the v_i/v_t criterion in all ECGs and all Brugada criteria, $^{\S}P < 0.05$, $^{\S\S}P < 0.01$, $^{\delta\delta\delta}P < 0.001$ for the fourth Brugada criterion vs. the v_i/v_t criterion applied in the fourth step.

The rationale behind the two new criteria and their potential value

The rationale behind the v_i/v_t criterion is that during WCT due to SVT, the initial activation of the septum should be invariably rapid and the intraventicular conduction delay causing the wide QRS complex occurs in the mid to terminal part of the QRS. Thus, the conduction velocity of initial ventricular activation should be faster than that of the later or terminal ventricular activation during SVT conducted with functional aberration or fixed BBB. During WCT due to VT, however, an initial slower muscle-to-muscle spread of activation occurs until the impulse reaches the His–Purkinje system, after which the rest of the ventricular muscle is more rapidly activated. Thus, in WCTs due to VT, the conduction velocity of initial ventricular activation is slower than that of the later ventricular activation. This assumption should hold true regardless of the mechanism of VT or presence or absence of structural heart disease. We used another assumption while devising the v_i/v_t criterion, that the steepness of the QRS (which was measured by voltage in millivolts, the impulse travelled in vertical direction during a given time period) is directly proportional with the conduction velocity of the propagating impulse in the ventricle. Antiarrhythmic drugs that impair conduction in the His–Purkinje system and/or ventricular myocardium (such as class I drugs and amiodarone) would be expected to decrease the v_i and v_t approximately to the same degree, therefore the v_i/v_t ratio will not change significantly. The reasons for misdiagnoses using the v_i/v_t criterion alone might be: (i) disorders involving the myocardium locally can alter the v_i or v_t, for example, a decreased v_i with unchanged v_t may be present in the case of an SVT occurring in the presence of an anteroseptal MI leading to the misdiagnosis of VT; or a scar situated at a late activated ventricular site may result in a decreased v_t in the presence of VT leading to the misdiagnosis of SVT; (ii) in the case of a fascicular VT, the v_i is not slower than the v_t; (iii) if the exit site of the re-entry circuit is very close to the His–Purkinje system, it might result in a VT with a relatively narrow QRS complex and the slowing of the v_i may last for such a short time that it cannot be detected by the surface ECG.

Because all 16 WCTs where the v_i/v_t criterion could not be applied proved to be VTs, the mere fact that the v_i/v_t criterion cannot be applied might indicate that the underlying mechanism of WCT is VT. However, this observation needs further confirmation.

The aVR criterion is not completely new in the sense that it is similar to the old QRS axis criterion, according to which the QRS axis in the right superior quadrant (-90° to $\pm 180^\circ$) suggests VT, because the resultant QRS vector should be -60° to $+120^\circ$ to give rise a predominantly positive QRS in lead aVR. However, the aVR criterion is different from the old QRS axis criterion not only in the minimal difference in QRS axis that is needed to have an *R* wave in lead aVR vs. a right superior quadrant axis, but also in the fact that our aVR criterion suggests VT only in the presence of an initial *R* wave in lead aVR. *Figure 8* demonstrates why the aVR criterion is different and may be superior to the QRS axis criterion. A WCT due to SVT is shown with a predominantly positive QRS complex in lead aVR, the QRS axis in the frontal plane is -160°, thus the QRS axis criterion suggests VT. However, the onset of the predominantly

Table 5 The overall TA, sensitivity, specificity, and predictive values of the new and Brugada algorithms in several subgroups

		Class I antiarrhythmic drugs or amiodarone $n = 151$		Pre-existent BBB $n = 141$		Class I antiarrhythmic drugs or amiodarone + pre-existent BBB $n = 84$		Idiopathic VT $n = 37$	
		New algorithm	Brugada criteria	New algorithm	Brugada criteria	New algorithm	Brugada criteria	New algorithm	Brugada criteria
Overall TA	%	**98.7**	**95.4**	**92.2***	**85.8**	**97.6****	**92.9**	**86.5****	**67.6**
	(95% CI)	*(96.9–100.5)*	*(92–98.7)*	*(87.8–96.6)*	*(80.1–91.6)*	($P = 0.063$) *(94.4–100.9)*	*(87.3–98.4)*	($P = 0.065$) *(75.5–97.5)*	*(52.5–82.7)*
Sensitivity for VT Dx	%	**100***	**95.9**	**98.3****	**92.2**	**100***	**93.8**	**86.5****	**67.6**
	(95% CI)	*(100–100)*	*(92.7–99.1)*	($P = 0.065$) *(95.9–100.7)*	*(87.3–97.1)*	*(100–100)*	*(88.4–99.1)*	($P = 0.065$) *(75.5–97.5)*	*(52.5–82.7)*
Specificity for VT Dx	%	**50**	**75**	**65.4**	**57.7**	**50**	**75**		
	(95% CI)	*(1–99)*	*(32.6–117.4)*	*(47.1–83.7)*	*(38.7–76.7)*	*(1–99)*	*(32.6–117.4)*		
(+) pred. val. for VT Dx	%	**98.7**	**99.3**	**92.6**	**90.6**	**97.6**	**98.7**	**100**	**100**
	(95% CI)	*(96.8–100.5)*	*(97.9–100.7)*	*(88–97.3)*	*(85.3–95.9)*	*(94.2–100.9)*	*(96.1–101.2)*	*(100–100)*	*(100–100)*
(−) pred. val. for VT Dx	%	**100*****	**33.3**	**89.5**	**62.5**	**100**	**37.5**		
	(95% CI)	*(100–100)*	*(2.5–64.1)*	*(75.7–103.3)*	*(43.1–81.9)*	*(100–100)*	*(4–71)*		
Sensitivity for SVT Dx	%	**50**	**75**	**65.4**	**57.7**	**50**	**75**		
	(95% CI)	*(1–99)*	*(32.6–117.4)*	*(47.1–83.7)*	*(38.7–76.7)*	*(1–99)*	*(32.6–117.4)*		
Specificity for SVT Dx	%	**100**	**95.9**	**98.3**	**92.2**	**100**	**93.8**		
	(95% CI)	*(100–100)*	*(92.7–99.1)*	*(95.9–100.7) (87.3–97.1)*	*(100–100)*	*(88.4–99.1)*			
(+) pred. val. for SVT Dx	%	**100**	**33.3**	**89.5**	**62.5**	**100**	**37.5**		
	(95% CI)	*(100–100)*	*(2.5–64.1)*	*(75.7–103.3)*	*(43.1–81.9)*	*(100–100)*	*(4–71)*		
(−) pred. val. for SVT Dx	%	**98.7**	**99.3**	**92.6**	**90.6**	**97.6**	**98.7**		
	(95% CI)	*(96.8–100.5)*	*(97.9–100.7)*	*(88–97.3)*	*(85.3–95.9)*	*(94.2–100.9)*	*(96.1–101.2)*		

Dx, diagnosis; pred. val., predictive value, 95% CI = 95% CI, *Significant ($P < 0.05$), **borderline significant difference between the new and Brugada algorithms. ***Significant difference in predictive values between the new and Brugada algorithms indicated by disjoint (non-overlapping) 95% CI. The missing values in the idiopathic VT column either could not be calculated, because the number of true negatives in VT diagnosis and that of true positives in SVT diagnosis were zeroes, or was no sense to calculate them (SVT diagnosis parameters).

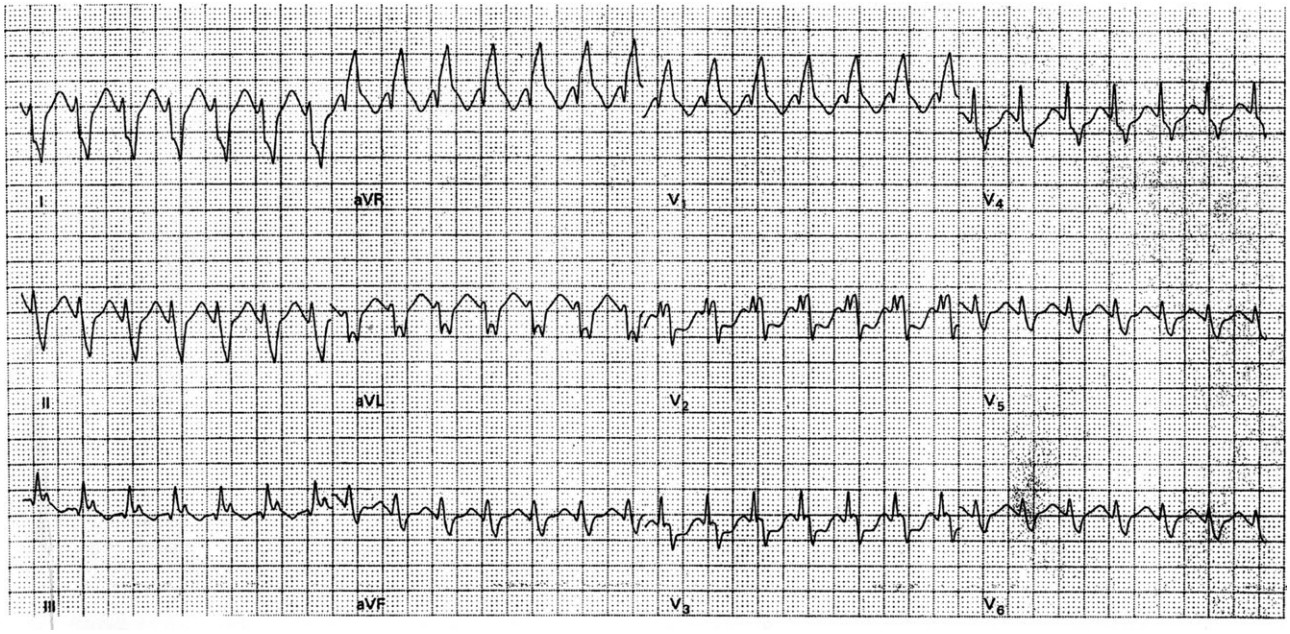

Figure 8 An example of a WCT due to SVT showing why the aVR criterion might be superior to the old QRS axis criterion.

positive QRS in lead aVR is negative (*Q* wave), therefore the aVR criterion did not suggest VT. A positive aVR criterion suggesting VT seems to exclude PXT: none of our 17 PXTs had a positive aVR criterion. However, this potential use of aVR criterion needs further testing. The observation that an initial *R* wave in lead aVR rules out PXT is consistent with the fact that activation of the ventricles over an accessory pathway proceeds from the base towards the apex of the heart yielding a negative QRS complex in lead aVR. An initial *R* wave may be present in lead aVR, resulting in an rS complex, as a normal variant or in the presence of inferior MI due to loss of initial inferiorly directed forces and reciprocal gain in unopposed superiorly directed forces. However, in normal sinus rhythm the R/S ratio in lead aVR should be <1 thus, an initial *R* wave should not be present.[20,21]

Possible explanation for the superiority of the new algorithm to the Brugada criteria

The fourth step of the Brugada algorithm involving the complicated morphological ECG criteria accounted for most [41/70(59%)] of incorrectly diagnosed WCT episodes. Although in the first three steps of the two algorithms the TAs were quite similar, the v_i/v_t criterion in the fourth step proved to be superior to the fourth Brugada criterion (having a significantly greater TA, sensitivity, and NPV for VT diagnosis, and specificity and PPV for SVT diagnosis). Another potential cause for the lower overall TA of the Brugada algorithm may be that it uses highly specific but relatively insensitive criteria (in this study the sensitivity for VT diagnosis of the four Brugada criteria in the order of their application was 22.8, 56.5, 10.1, and 39.4%, respectively) and the criteria of the new algorithm are not only highly specific but some of them have a good sensitivity (the sensitivity of the BBB, fascicular block criterion was 74.7% and that of the v_i/v_t criterion in the fourth step was 70% in VT diagnosis). Furthermore, it was shown[18] that the presence of pre-existing BBB and the use of class I antiarrhythmic drugs or amiodarone result in a low specificity of the second Brugada criterion (i.e. in many of these patients with WCT due to SVT, the longest R-to-S interval in the precordial leads will be >100 ms suggesting the misdiagnosis of VT). However, pre-existing BBB and class I drug or amiodarone treatment are not expected to influence the v_i/v_t criterion or any other criteria of the new algorithm.[1] Indeed, in 8/30 (27%) SVTs that were present in patients taking either class I antiarrhythmic drugs or amiodarone or having pre-existent BBB, the longest R-to-S interval was >100 ms in our study. Also consistent with this finding, our results showed that in the presence of pre-existent BBB the overall TA of the new algorithm was superior to that of the Brugada criteria. Another weak point of the RS >100 ms Brugada criterion is that the RS interval during idiopathic intrafascicular tachycardia is 60 to 80 ms, therefore these VTs cannot be correctly diagnosed using the second Brugada criterion.[22–24] Among all idiopathic VTs in our study, the longest R-to-S interval was <100 ms in 15/29 (52%) cases. As noted previously, the new algorithm demonstrated a borderline superior overall TA compared with that of the Brugada criteria in the presence of idiopathic VT.

Limitations

The new algorithm is inherently unable to recognize certain forms of WCT. Bundle branch re-entry VT, fascicular VT, and SVT involving an atriofascicular accessory pathway are associated with typical BBB pattern indistinguishable from that associated with SVT with functional aberrancy or pre-existent BBB,[1,2,10,25] unless A–V dissociation is present. Another limitation of the new algorithm is the somewhat arbitrary definition that v_i/v_t should be measured in the lead where initial ventricular activation is the fastest. The underlying premise was that, in VT, the v_i/v_t should be <1 even if the v_i is measured in the lead where its value is the greatest. The Brugada criteria are not widely accepted as standard for WCT evaluation, thus, the superiority of the

new to the Brugada algorithm demonstrated in this study does not necessarily imply that the new algorithm may be the best current method for WCT evaluation. However, Brugada *et al*.[7] claimed that their algorithm had a better sensitivity and specificity than the traditional criteria without providing a true head-to-head comparison of the two methods in their study. Although other authors[1,10,18] reported a lower sensitivity and specificity of the Brugada algorithm than those originally reported by Brugada *et al*.[7] they still found the Brugada citeria useful and the claim that the Brugada criteria are superior to the traditional criteria was neither confirmed nor refuted in a study using a head-to-head comparison of the two methods.

Conclusions

By using all published ECG criteria, the underlying cause of regular WCTs is still misdiagnosed in up to 10% of patients. It seems prudent to consider and treat all sustained, regular WCTs as VT unless the diagnosis of SVT can be definitely established, because it is far better to be wrong with a few cases of SVT treated as VT than the reverse situation, since treating a VT as SVT may result in potentially disastrous consequences (e.g. iv verapamil injection may cause severe hypotension and/or VT acceleration and ventricular fibrillation[2,26,27]). The proposed new algorithm, which includes two new ECG criteria, may be useful to improve our diagnostic accuracy.

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Conflict of interest: none declared.

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