Communications

Discrimination of ventricular tachycardia from sinus tachycardia by antitachycardia devices: value of median filtering

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ABSTRACT

Rate and rate variation algorithms used by implantable devices designed for management of life-threatening arrhythmias have major limitations in separating physiologic sinus tachycardia (ST) from pathologic ventricular tachycardia (VT) requiring therapy. These algorithms presently utilize criteria such as simple heart rate, stability of rate, or derivative of rate (sudden onset) which assumes a gradual onset for ST and an abrupt onset for VT. An alternative method employing median filtering was designed, tested, and compared to a previously published sudden onset rate algorithm using the same data set for analysis of performance. In 50 patients, the onset of ST during exercise and onset of VT were analysed. To accommodate occasional outlying intervals which might affect rate derived by averaging, a five-cycle median filter was used to smooth heart rate. Results from using a 'fixed-interval' or a 'percent' change in the median gave better discrimination of ST and VT than previously published 'fixed-interval' or 'percent' change algorithms. The superiority of median filtering performance was validated by statistical measures.

Keywords: Sudden onset, median filtering, ventricular tachycardia

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INTRODUCTION

Pacing and non-pacing antitachycardia devices (ATDs) have emerged as popular options to treat tachyarrhythmias such as ventricular fibrillation (VF) and ventricular tachycardia (VT)[1]. These devices have been shown to perform well in terminating VF and VT but often mistakenly diagnose benign arrhythmias such as sinus tachycardia (ST) as VT, resulting in inappropriate shocks[2]. Many methods have been proposed to solve the ST versus VT problem, including waveform (morphologic) methods. However, due to their heavy computational demands, these morphologic methods[3,4] as well as combination of timing and morphology algorithms[5,6,7] to detect for tachyarrhythmias have not yet been incorporated. Rate analysis remains the sole criterion for detecting pathologic tachyarrhythmias requiring treatment at present.

Current devices use a combination of four rate analysis methods[8,9,10] including high rate (a run of consecutive short interventricular intervals), sudden onset (an acute decrease in interventricular interval), sustained high rate (a continuation of consecutive short interventricular intervals), and rate stability (a small variance in interventricular intervals). Despite their usage in current generation devices, these rate methods still have limitations in separating benign ST from pathological paroxysmal VT requiring therapy. Cases of incorrect diagnoses and consequently incorrect therapies have been well documented[11].

From published studies, ST has been found to have a slow and gradual onset while VTs often have abrupt beginning. Warren *et al.*[12] examined the effectiveness of absolute rate and rate variation in distinguishing ST from VT. It was found that high rate combined with a sudden onset criterion gave the best results using false detection of VT as a performance measure (3%). However, the study regarded only results of ST analysis and did not test the performance of the sudden onset criterion in VT cases. In contrast, Olson *et al.*[10] examined performance of VT detection by a sudden onset criterion but did not analyse ST. A data base of both STs and VTs was provided by Fisher *et al.*[13] who investigated the statistics of cycle lengths from both ST and VT.

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Brown *et al.*[14] assessed the performance of two sudden onset algorithms[8,15] using the data published by Fisher *et al.*[13]. They concluded that the trade-offs between sensitivity versus specificity of VT discrimination from ST using sudden onset criteria made such criteria unfeasible for practical implementation. The sudden onset methods analysed by Brown *et al.*, however, examined only individual cycle lengths, which are extremely sensitive to random variations. Such variations result in a high incidence of false positives. Averaging consecutive cycle lengths might appear to give a better indication of the true underlying rate. However, averaging causes rate 'smoothing' and, as a consequence, possible loss of the 'sudden onset' transition from sinus rhythm to a paroxysmal tachycardia.

As an alternative to the above methods, the use of the median of the rate for recognising sudden onset was examined. Compared to averaging methods which tend to smooth the difference between consecutive mean rates, median filtering manages to preserve abrupt change in rate, or 'sudden onsets'[16,17]. Using the median, one can improve detection of abrupt changes in the rate while ignoring effects of occasional or isolated ectopic depolarizations.

In the present study, a new sudden onset criterion using the cycle length median has been designed, tested, and compared to sudden onset rate algorithms previously published. Comparative analysis was performed on the same data set used for analysis of earlier published methods by Brown *et al.*[14].

MATERIALS AND METHODS

Materials

The test data for this study consisted of 100 total cases from Fisher *et al.*[13]: 50 cases of ST and 50 cases of VT. The 50 sinus tachycardia cases were recorded from 50 healthy subjects starting from rest rushing up a flight of 100 stairs. The 50 spontaneous VT cases also came from 50 patients and were confirmed by electrophysiology studies or standard ECG criteria. The Fisher study charted 5 cycle lengths prior to tachycardia as well as the first to the sixth cycle lengths following onset of tachycardia.

Median filtering

In this study, five-point median filtering was applied to intervals in an effort to recognise tachycardia episodes, and the absolute value of the interval difference between the running medians were calculated to characterize onset. A 5-point median was chosen because a shorter number of intervals would be more susceptible to isolated ectopic events and consecutive premature contractions and because a larger number of intervals while giving the same correct results could unnecessarily delay the diagnosis.

If the change in median rate exceeded the sudden onset criterion, diagnosis was determined to be paroxysmal VT, otherwise a gradual onset was inferred and the diagnosis was ST. Two types of empirically derived criteria were examined separately on the test data (from the Fisher study). The first set is a *fixed interval* change of 100 ms, 150 ms, 200 ms, 250 ms, and 300 ms. If the difference in consecutive medians exceeded the determined fixed interval, then VT was diagnosed, otherwise ST was concluded. The second set of criteria consisted of *decreases in percentage* from the previous median value of 10%, 20%, 25%, 30%, and 40%. Similar to the fixed-interval criterion, if the decrease in percent value from an immediately previous median exceeded the set threshold, then VT was decided, otherwise ST was diagnosed. Data from the Fisher study[13] were entered into a data base and submitted to two variations of the median filter algorithm as described above.

Receiver operating characteristic curves

Receiver Operating Characteristic (ROC) curves[18] were utilized as performance measures of each of the threshold criteria for both cases, fixed-interval and percent change. For this study, sensitivity (probability of detection of VT) was plotted versus *one minus the specificity* (probability of failure to detect ST) to assess the performance of the median filter method versus previously published algorithms. It has been demonstrated[19] that the area under the ROC curves corresponds to the percent of correct decisions when given both ST and VT cases for examination. Perfect performance would give an area of 1 (or 100%), while chance would give 0.5 (or 50%). Calculation of the area under the ROC curve by the trapezoid method[20] was used (with no curve-fitting since no distribution of the parameters examined can be assumed) to compare the performance of our median technique versus the Brown analysis of two earlier methods.

Statistical significance for the difference in the areas under the ROC curves for the fixed-interval versus percent change criteria was sought. A criterion developed for medical imaging applications was used for this study[21,22]:

$$z = \frac{A_1 - A_2}{\sqrt{SE_1^2 + SE_2^2 - 2rSE_1SE_2}} \tag{1}$$

where A_i and SE_i refer to the observed area and estimated standard error of the ROC curve associated with a particular criterion, and r represents the estimated correlation between A_1 and A_2. Standard error (SE) can be calculated as [21]:

$$SE = \sqrt{\frac{A(1-A)+(n_s-1)(Q_1-A^2)+(n_v-1)(Q_2-A^2)}{n_s n_v}} \tag{2}$$

with A = area under ROC curve, n_s = number of ST samples, n_v = number of VT samples, and Q_1 and Q_2 being:

$$Q_1 = \frac{A}{(2-A)} \tag{3}$$

$$Q_2 = \frac{2A^2}{(1 + A)} \qquad (4)$$

Using this, we obtain standard errors for each area under the curve.

To calculate z, we also need the correlation due to using the same data base between the two compared methods. The correlation can be computed by a lookup table in[22] with the parameters $A_1 + A_2$ and $r_v + r_s$. The parameter r_v represents the correlation factor due to the same VT base being used for testing, and r_s the correlation factor due to using the same ST measures. This correlation is done using Pearson product moment analysis of two arrays of points, one array being the performance measure values obtained from one method, and the other array performance measure values obtained from a second method. Once r is calculated, the performance value z can be computed (see Equation 1).

RESULTS

Results from the median fixed-interval sudden onset are shown in *Table 1*. A trade-off exists between specificity and sensitivity of performance. With 100 ms as the criterion, the median filter method achieved only 68% ST detection (specificity) but high sensitivity of 96% VT detection. As the interval criterion is increased, it becomes more difficult to detect VT but easier to identify ST, such that a 300 ms threshold gives 100% ST detection but only 46% VT detection. Similar results are shown with varying median percent changes used as the sudden onset criteria (see *Table 2*). With a low onset criterion value of 10% change, a high VT detection sensitivity of 100% was achieved but resulted in an unacceptable specificity value of 18%. At the other extreme with 40% change selected as sudden onset criterion, a high specificity of 100% was achieved but sensitivity dropped to 46%.

Figure 1 compares the performance from the fixed-interval versus percent change criteria using a five-point median filter. The ideal point would be at 0% false detection and 100% VT detection. From the graph, the percent change curve appears to perform better because the ROC curve is closer to the ideal point. For the same probability of VT detection, percent change has lower false positives. For the same level of false detection, percent change has a higher percentage of VT detection. Using the area under the ROC curve as measure of performance, the median percent change has a percent correct (P_c) of 96.8%, while the median fixed-interval only 93.2%.

Table 1 Fixed-interval sudden onset results

	Fixed Interval Sudden Onset					
	Real ST (50 cases)			Real VT (50 cases)		
Interval	ST	VT	SPEC	ST	VT	SENS
100 ms	34	16	68%	2	48	96%
150 ms	46	4	92%	10	40	80%
200 ms	48	2	96%	14	36	72%
250 ms	49	1	98%	22	28	56%
300 ms	50	0	100%	27	23	46%

Separation of sinus tachycardia (ST) from ventricular tachycardia (VT) using a sudden onset criterion of fixed interval change from the previous median value (5 point median). Criterion satisfaction would indicate VT diagnosis, otherwise ST is selected. SENS = Sensitivity of VT Detection, SPEC = Specificity of VT Detection.

Table 2 Percent-change sudden onset results

	Percent Change Sudden Onset					
	Real ST (50 cases)			Real VT (50 cases)		
% Change	ST	VT	SPEC	ST	VT	SENS
10%	9	41	18%	0	50	100%
20%	43	7	86%	2	48	96%
25%	48	2	96%	4	46	92%
30%	49	1	98%	15	35	70%
40%	50	0	100%	27	23	46%

Separation of sinus tachycardia (ST) from ventricular tachycardia (VT) using a sudden onset criterion of percent change from the previous median value (5 point median). Criterion satisfaction would indicate VT diagnosis, otherwise ST is selected. SENS = Sensitivity of VT Detection, SPEC = Specificity of VT Detection

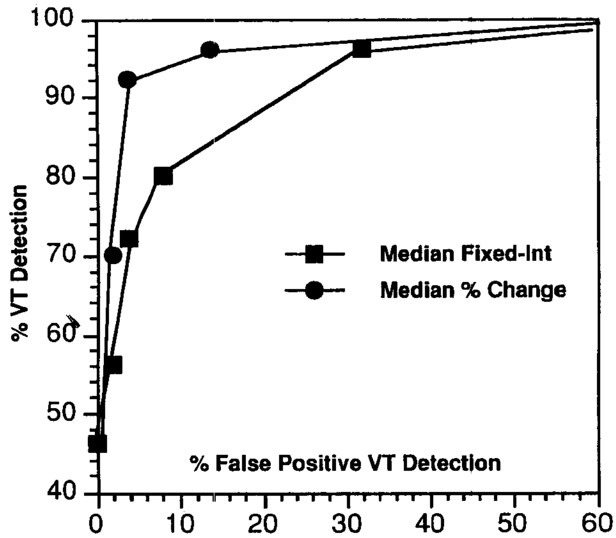

Figure 1 Receiver operating characteristic curves of the two median filter criteria. The horizontal axis contains the percent of false positive detections of ST as VT and the vertical axis contains percent correctly identifying VT as VT. The ideal point of 100% correct identification of VT and ST is the top left hand corner. Data points with different thresholds are represented as circles (median percent) and square blocks (median fixed-interval). The curves are drawn by connecting the data points by linear interpolation

Results from the Brown study[14] were compared to the two median criteria in *Figures 2* and *3*. *Figure 2* contains curves using a fixed-interval criterion and Brown's fixed-interval analysis. One sees that the median fixed-interval curve performs better by inspection and is confirmed by a P_c value of 93.04% and 88.2%. Figure 3 compares curves from the median technique using a percent change and Brown's percent change analysis. In this case, the median percent change curve performs better with a P_c value of 96.82% versus 95.16% for the earlier algorithm. The Brown percent change criterion curve performs better than the median fixed-interval curve, but still worse

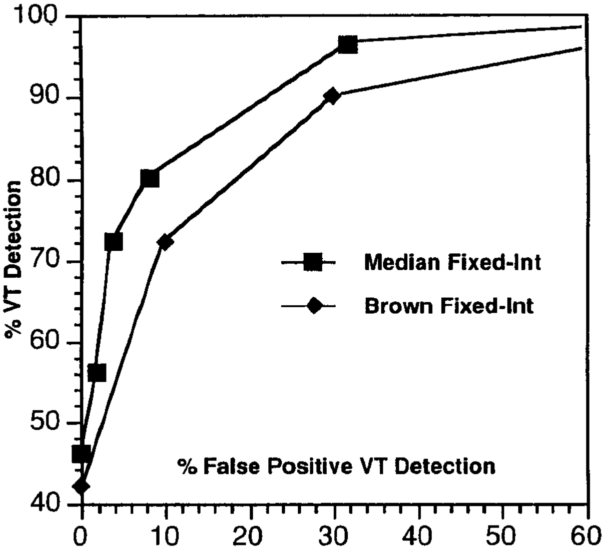

Figure 2 Receiver operating characteristic curves of the Brown fixed-interval and the median fixed-interval criteria. The Brown curve contains points represented by diamonds, and the median fixed-interval curve by square block points

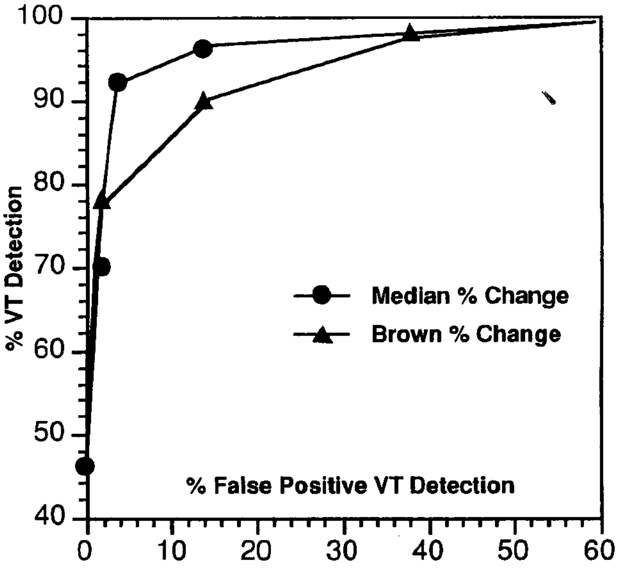

Figure 3 Receiver operating characteristi curves of the Brown percent and the median percent criteria. The Brown curve contains points represented by triangles, and the median percent curve by circles

Table 3 Areas and standard errors for criteria tested

	A	SE
Fix Brown	0.8820	0.0348
% Brown	0.9516	0.0224
Fix Med	0.9318	0.0266
% MEd	0.9682	0.0181

Fix = Fixed-Interval Change, % = Percent Change, Med = Median Filter, Brown = Brown Study, A = Area under ROC curve, SE = Standard Error

Table 4 The z value for comparing different methods

	r_s	r_p	r	z	p value
Median % vs. Median Fix	0.88	0.95	0.86	2.52	0.0059
Median Fix vs. Brown Fix	0.98	0.41	0.63	5.08	0.0001
Median % vs. Brown %	0.59	0.71	0.51	0.81	0.209

r_v = correlation between the compared methods using the same VT data base;
r_s = correlation between the compared methods using the same ST data base;
r = overall correlation due to r_v, r_s, and the areas; z = performance value; p = Probability that the difference in area (performance) is due to random occurrence; Fix = Fixed-Interval; % = Percent Change; Med = Median Filter; Brown = Brown Study

than the median percent change curve. Therefore, the median filter percent change has the best overall performance of all four criteria tested.

To obtain statistical significance for the difference in performance, we obtained the standard errors for each area under the curve and list them in *Table 3*. The value z is compared to the normal distribution table for statistical significance ($p < 0.05$ significance has the value of 1.65). The final comparison is shown in *Table 4*. For the median percent change versus the median fixed-interval, the differences in P_c is statistically significant with $p < 0.05$. Similarly, for the median fixed-interval versus the Brown fixed-interval, the performance measure P_c is also statistically significant with $p < 0.05$. One can conclude from the above two comparisons that the median percent change performs better than the Brown fixed-interval algorithm. Only the median percent change versus the Brown percent change comparison did not yield a statistically significant conclusion. From a table in[21], the number of samples needs to be doubled for achieving $p < 0.05$ for the Brown percent change versus the median percent change.

DISCUSSION

From initial assessment, the use of median filtering appears to offer some improvement over previously published results. The median percent change appeared to perform the best amongst three other criteria, with the differences in performance validated statistically in two of the other three methods considered.

The original rationale for using the median as opposed to the average is that while both de-emphasise outliers, the average tends to smooth the rate and the median performs better in preserving true edges, or 'sudden onsets'. By using the median, one can avoid false positive detection of VTs in the face of isolated or consecutive ventricular premature depolarisations. The median is also less sensitive to errors in false recognition of a cardiac event since it treats these events as outliers.

In this preliminary study, median filtering has been used to separate ST from VT based on the 'suddenness' of onset. Performance of this algorithm is slightly superior than previous onset algorithms, but needs more cases for statistical verification.

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