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MEASUREMENT

Comparison of automatic QT measurement techniques in the normal 12 lead electrocardiogram

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Abstract

Objective—**To undertake a quantitative assessment of different automatic QT measurement techniques and investigate the influence of electrocardiogram filtering and algorithm parameters.**

Design—**Four methods for identifying the end of the T wave were compared: (1) threshold crossing of the T wave (TH); (2) threshold crossing of the differential of the T wave (DTH); (3) intercept of an isoelectric level and the maximum T wave slope (SI); and (4) intercept of an isoelectric level and the line passing through the peak and the point of maximum slope of the T wave (PSI). Automatic QT measurements were made by all techniques following different electrocardiogram filtering and, when appropriate, with four different isoelectric levels and with three different threshold levels.**

Subjects—**12 simultaneous standard electrocardiogram leads, containing at least two electrocardiogram complexes, were recorded from 25 healthy volunteers relaxing in a semirecumbent position.**

Main outcome measure—**Mean and standard deviation of differences between reference and automatic QT measurements were compared for the four techniques.**

Results—**The mean automatic QT measurements varied by up to 62 ms, which was greater than has been found between manual measurements by experienced clinicians. Technique TH was particularly poor. The other techniques produced consistent results for most electrocardiogram filter, isoelectric level, and threshold level settings; but technique SI underestimated QT relative to the other techniques.**

Conclusion—**Different QT measurement techniques produced results which were influenced, to varying degrees, by filtering and technique variables. This is relevant for the inter-comparison of studies using different techniques. Technique TH, a common approach, is not recommended.**

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Keywords: QT interval; electrocardiography; automatic QT measurement techniques

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The QT interval is an important electrocardiogram feature that currently is a subject of great interest as a clinical predictor of arrhythmia risk.[1–3] It is a non-invasive measure of ventricular repolarisation time and has been recognised since the earliest history of electrocardiology. A single global QT interval measurement from the 12 lead electrocardiogram has been the standard measure, but recently there has been great interest in the distribution of the QT intervals across the 12 electrocardiogram leads. This feature, QT dispersion, is believed to reflect local repolarisation abnormalities[3–5] and is emerging as an important new clinical tool.

Manual QT interval measurement is tedious and labour intensive, depending on callipers, rulers, or digitising tablets. The end of the T wave is often difficult to determine as the return to the baseline of the slow moving deflection, often contaminated with noise, must be identified. It is not surprising, therefore, that inter-operator differences of between 10 and 28 ms have been reported,[6–8] although the range of differences is perhaps less than might be expected. A reliable automatic QT measurement technique would be a major assistance. It would be labour saving, but more importantly, it would remove subjectivity from the measurement.

Some researchers have developed their own algorithms for automatic QT interval analysis,[6,7] while others have extended frequently reported methods without further evaluation.[9–11] Currently, the main general algorithms for determining the end of the T wave include the interception of a threshold level and the T wave, the interception of a threshold level and the differential of the T wave, and the interception of a line characterising the slope of the end of the T wave and the isoelectric level. Variations applied to these general algorithms include differences in signal preprocessing, threshold, and isoelectric levels and the method of slope characterisation. Individual techniques have been validated against the current gold standard, manual measurement.[6,7] There are, however, little data on how the different algorithms compare against each other, and even less information on the factors which influence measurement of the QT interval. As a result of the methodological differences, direct comparison of published QT data from different groups is often difficult.[12]

The aim of this study was to undertake a quantitative assessment of different automatic QT measurement techniques. The effects of changing electrocardiogram filtering and the parameters of the different algorithms were also investigated.

Methods

DATA COLLECTION

Twenty five individuals with no history of heart disease were recruited to the study (all men aged from 19 to 50 years). Simultaneous 12 lead electrocardiograms were amplified (gain 1000, bandwidth 0·05–100 Hz) and digitally sampled at 500 Hz while the participants were relaxed in a semirecumbent position. The use of good quality electrocardiograms recorded from healthy individuals in this initial study enabled optimum performance of the algorithms to be quantified. Ten seconds of electrocardiogram data were acquired using a microcomputer (Opus 386) fitted with a 12 bit analogue to digital converter (Metrabyte DAS 16) giving a resolution of 2·44 μV. A section free from baseline drift artefact and containing two full electrocardiogram complexes was selected from the sampled electrocardiogram data of each subject. This provided 600 electrocardiogram complexes (25 subjects × 12 leads × two complexes) for manual and automatic analysis.

MANUAL ANALYSIS

Data plotting

The electrocardiograms were plotted to paper using a Hewlett Packard Laserjet III with a resolution of 118 dots/cm. The plots had a vertical (voltage) scale equivalent to 10 mm/mV and a horizontal (time) scale equivalent to 50 mm/s.

QT measurement

Manual measurement was performed by an experienced researcher who identified the R wave onset and T wave offset on each electrocardiogram complex using a digitising tablet as described elsewhere.[13] A preliminary validation study had compared the researcher with QT measurements calculated from the mean of four cardiologists' measurements. Across all measurements the mean difference between the researcher and the cardiologists was only 7 ms with a standard deviation of 23 ms. As the prime interest of this study was the difference in QT measurements between automatic techniques, with manual measurements used simply as a reference to facilitate the comparison, the need for manual measurements from more than one observer was unnecessary. The use of a single automatic technique as a reference was discounted as it would have been impossible to calculate the random error associated with that technique and with its different electrocardiogram filtering and algorithm parameters. In addition, the random errors of similar techniques would have been artificially reduced. The use of a manual reference inevitably increased the calculated errors but in a similar way across all techniques.

AUTOMATIC QT MEASUREMENT

Electrocardiogram filtering

Four filtered versions of each electrocardiogram record were generated with the following bandwidths; 0·05–40 Hz, 0·1–40 Hz, 0·25–40 Hz, and 0·5–40 Hz. Filtering was achieved using a second order Butterworth recursive digital filter. The original and filtered electrocardiograms were differentiated using a two point difference method.

AUTOMATIC FEATURE IDENTIFICATION

Each of the automatic QT measurement techniques required prior knowledge of the location of certain features of the electrocardiogram waveforms. Software was developed to identify the following features: P, R, and T wave peaks, R wave onset, RR interval, isoelectric levels, and maximum T wave slope.

Identification of the P, R, and T wave peaks was achieved using the approximate locations of the peaks in the original electrocardiogram, identified manually using interactive software. The actual peak values in the original and filtered data were found by searching for the maximum positive or negative value, depending on the polarity of the electrocardiogram wave under analysis, in close proximity to the approximate locations. The R wave onsets for all electrocardiogram complexes were determined by finding a threshold crossing point of the differentiated electrocardiogram in the PR segment. The threshold level used was one tenth of the maximum of the differentiated electrocardiogram in the PR segment. The positions of these electrocardiogram features, as determined by automatic analysis, in the minimally and maximally filtered electrocardiograms (0·05–100 and 0·5–40 Hz bandwidths respectively), were verified by manual inspection.

The RR interval was calculated as the average RR interval from lead I. On this basis an upper limit for the QT interval was determined from the expected QT interval, calculated using Bazett's formula,[14] plus one fifth of the RR interval. The PR isoelectric level was determined from the average of short flat noise free segments in the PR interval. This was achieved by identifying the five sets of 10 consecutive samples, in the PR segment, with the lowest standard deviations and calculating the isoelectric level as the mean of the five set means. This was repeated for the TP segment. A mean isoelectric level (M) was calculated as the average of the PR and TP levels. An additional isoelectric level (X) was taken as the value of a single point 40 ms preceding the R onset. For each electrocardiogram complex, the position and value of the point of maximum slope of the T wave deflection after the T wave peak were calculated. The point of maximum slope was determined from the location of the maxima in the differential electrocardiogram data between the T wave peak and the calculated upper limit for the QT interval.

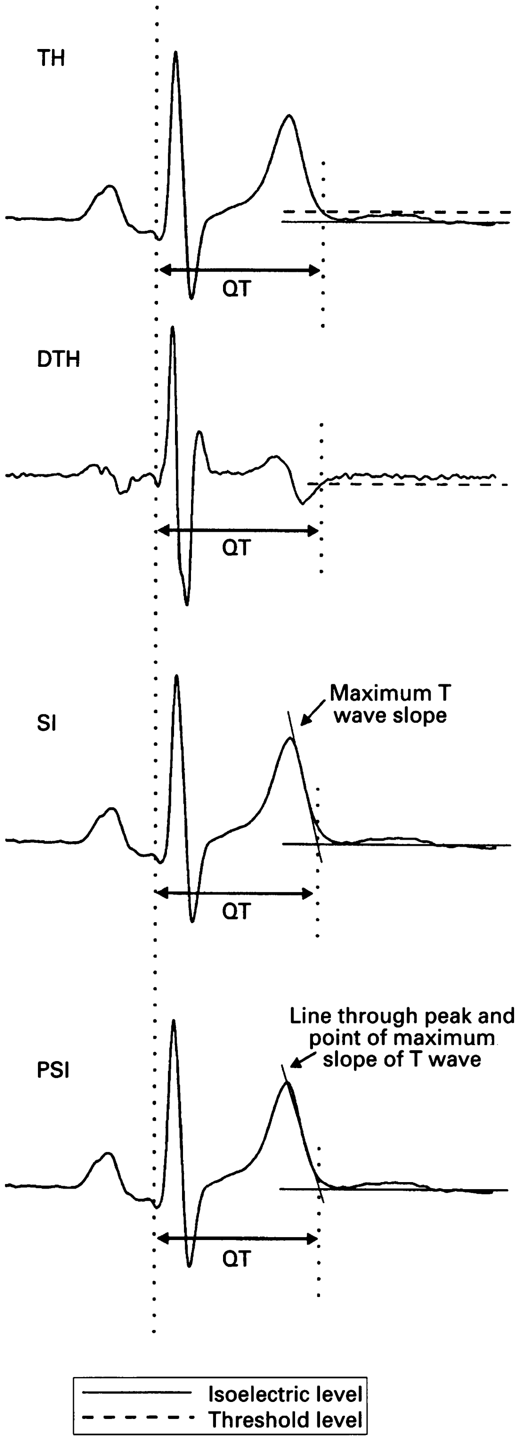

Figure 1 Automatic QT measurement techniques. TH, threshold; DTH, differential threshold; SI, slope intercept; PSI, peak slope intercept.

Table 1 Electrocardiogram filter and algorithm parameter combinations used in comparison of automatic QT measurement techniques

Electrocardiogram bandwidth (Hz)	Algorithm parameters: Isoelectric level	Algorithm parameters: Threshold level	Technique
0·05–100	TP	0·10	All
0·05–40	*TP*	*0·10*	All
0·1–40	TP	0·10	All
0·25–40	TP	0·10	All
0·5–40	TP	0·10	All
0·05–40	*TP*	*0·10*	TH, SI, PSI
0·05–40	PR	0·10	TH, SI, PSI
0·05–40	M	0·10	TH, SI, PSI
0·05–40	X	0·10	TH, SI, PSI
0·05–40	TP	0·05	TH, DTH
0·05–40	*TP*	*0·10*	TH, DTH
0·05–40	TP	0·15	TH, DTH

Isoelectric levels: M (mean of TP and PR isoelectric levels), X (single point 40 ms preceding R onset). TH, threshold; DTH, differential threshold; SI, slope intercept; PSI, peak slope intercept. Nominal standard settings are given in italics.

QT measurement

Automatic determination of the T wave end was by four techniques (fig 1). Techniques threshold (TH) and differential threshold (DTH) determined the T wave end as the interception of a threshold level with the T wave (technique TH) and the differential of the T wave (technique DTH). The threshold levels were calculated as a fraction, in the range 0·05–0·15, of the amplitude of the T wave or differential T wave for TH and DTH respectively. Threshold crossing points were determined using a left to right scan of the data from the waveform peaks. For technique TH the T wave amplitude and threshold level were calculated relative to an isoelectric level to allow for any baseline offsets. The final two algorithms were based on slope features of the T wave. Technique slope intercept (SI) identified the end of the T wave as the intercept of an isoelectric level and a line tangential to the point of maximum T wave slope. Technique peak slope intercept (PSI) calculated the end of the T wave as the intersection point between an isoelectric level and the line which passes through the peak of the T wave and the point of maximum T wave slope.

Data analysis

The QT intervals of all the electrocardiograms (original and filtered) of each participant were analysed using the four automatic techniques with a fixed set of algorithm parameters (threshold level 0·1, isoelectric level TP). In addition, the 0·05–40 Hz bandwidth electrocardiograms were analysed across a range of threshold levels (0·05, 0·1, and 0·15) and isoelectric levels (TP, PR, M, and X). Table 1 gives the resulting 12 combinations of filtér bandwidth and algorithm parameters. Automatic QT difference was defined as the difference between a QT interval measured automatically and the manual measure of the same interval. For each technique the mean (SD), across all QT intervals, of the automatic QT difference was calculated for each relevant filter/parameter combination (see table 1). In addition, the number of automatic QT measurement failures was recorded for the different techniques for each relevant combination. A measurement failure was identified as a QT measurement which exceeded the calculated upper limit of the QT interval, and the failure ratio was the number of failed measurements divided by the total number of measurements (600).

As so many inter-comparisons were possible, no statistical analysis has been carried out. Instead, the data were examined for general trends which made sense in the context of the overall data.

Results

Figure 2 compares the automatic QT measurement techniques. The sections of fig 2 show the mean (SD) of automatic QT differences ($mean_{AQD}$ and SD_{AQD}) and failure ratios for the different electrocardiogram bandwidths, isoelectric levels, and threshold levels for each technique.

ELECTROCARDIOGRAM FILTERING

Reducing the low pass cut off point from 100 to 40 Hz increased the $mean_{AQD}$ for technique DTH by 28 ms, while the $mean_{AQD}$ values of other techniques were shifted only marginally ($\leqslant$5 ms). SD_{AQD} was reduced for techniques DTH, SI, and PSI by 11 ms, 15 and 8 ms respectively. Increasing the high pass cut off from 0·05 to 0·5 Hz reduced $mean_{AQD}$ values for techniques TH by 31 ms, SI by 13 ms, and PSI by 21 ms, but had a smaller effect on technique DTH. Only small changes in SD_{AQD} were noted. The failure ratio for techniques TH and DTH remained at zero across all filter settings. The failure ratios of techniques SI and PSI at filter bandwidth 0·1–40 Hz were 0·003 and 0·013 respectively. The absence of a 40 Hz low pass cut off resulted in a number of failed measurements for technique PSI (failure ratio 0·003).

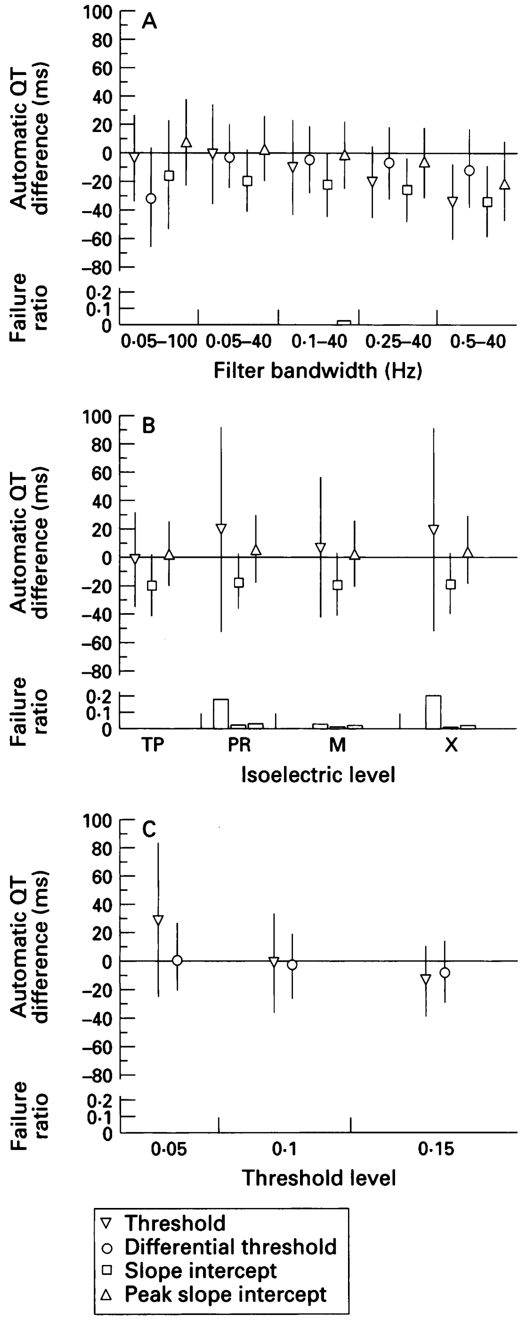

Figure 2 Mean and standard deviation of automatic QT differences and failure ratios with different (A) ECG filtering, (B) isoelectric levels and (C) threshold levels. Isoelectric levels: M (mean of TP and PR isoelectric levels), X (single point 40 ms preceding R onset).

Table 2 Maximum and minimum automatic QT differences ($mean_{AQD}$ and SD_{AQD}) for each technique.

	$Mean_{AQD}$ (ms)		SD_{AQD} (ms)	
Technique	Max	Min	Max	Min
TH	18 (III)	−17 (aVR)	85 (V1)	9 (I)
DTH	6 (II)	−25 (V1)	41 (V1)	7 (II)
SI	4 (III)	−32 (aVR)	46 (III)	6 (II, aVR, V6)
PSI	22 (aVL)	−11 (aVR)	53 (V1)	9 (aVR, V6)

*Fixed parameters (bandwidth 0·05–40 Hz, threshold level 0·1, isoelectric level TP) were used by each technique. The lead in which the maximum/minimum value was found is given in parenthesis. TH, threshold, DTH, differential threshold; SI, slope intercept; PSI, peak slope intercept.

ISOELECTRIC LEVELS

Both the $mean_{AQD}$ and SD_{AQD} for techniques SI and PSI varied by less than 4 ms across the isoelectric levels. Larger changes occurred across isoelectric levels for technique TH, particularly with the PR isoelectric level ($mean_{AQD}$ 22 ms, SD_{AQD} 39 ms) and for the X isoelectric level ($mean_{AQD}$ 22 ms, SD_{AQD} 37 ms) with respect to the TP level. Technique TH failure ratios of 0, 0·19, and 0·21 were found with TP, PR, and X isoelectric levels.

THRESHOLD LEVELS

For technique TH increments in the threshold level from 0·05 to 0·15 reduced the $mean_{AQD}$ and SD_{AQD} by 43 ms and 30 ms respectively. Small changes in $mean_{AQD}$ (−9 ms) were noted for technique DTH with little change in SD_{AQD} over the threshold range.

ELECTROCARDIOGRAM LEADS

Table 2 lists the range of automatic QT differences across the electrocardiogram leads for each technique using nominal standard filter and algorithm parameters (bandwidth 0·05–40 Hz, threshold level 0·1, isoelectric level TP). The magnitudes of the inter-lead ranges for $mean_{AQD}$ were similar for each technique and were 35, 31, 36, and 33 ms for techniques TH, DTH, SI, and PSI, respectively. The ranges for SD_{AQD} were less closely grouped and were 76 (TH), 34 (DTH), 40 (SI), and 44 ms (PSI). It is interesting to note that the largest or second largest values for SD_{AQD} for all of the automatic techniques occurred for electrocardiogram lead V1. V1 also had the lowest mean T wave amplitude.

OVERALL

Figure 3 shows the range of $mean_{AQD}$ and SD_{AQD} values for each technique with different electrocardiogram filtering and algorithm parameters. The intra-technique ranges of $mean_{AQD}$ for techniques TH, DTH, SI, and PSI, respectively, were 29 to −33 ms, 2 to −31 ms, −16 to −33 ms, and 7 to −19 ms. The greatest influences on the $mean_{AQD}$ values were the threshold level for technique TH, the low pass cut off for technique DTH, and the high pass filter cut off point for techniques SI and PSI. Similarly the intra-technique SD_{AQD} ranges and main influences were 74 to 35 ms (isoelectric level) for TH, 35 to

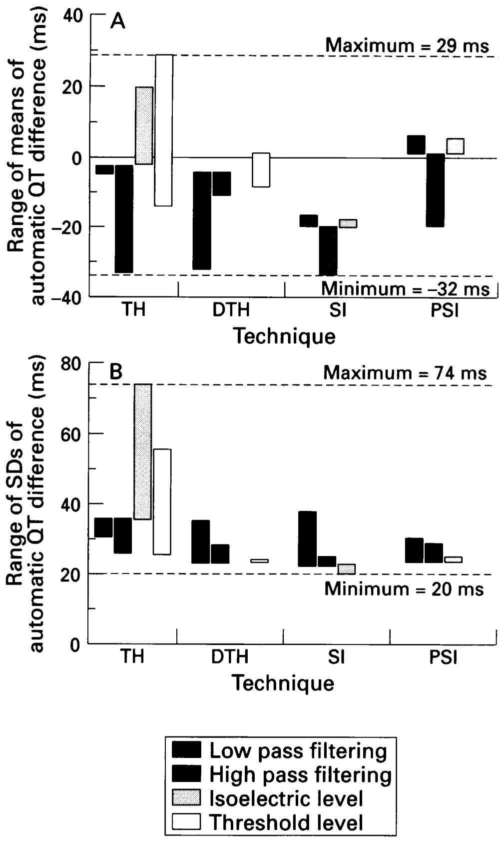

Figure 3 Maximum and minimum limits of automatic QT difference for (A) mean$_{AQD}$ and (B) SD$_{AQD}$ for each automatic technique across low pass filtering (0·05–100 and 0·05–40 Hz), high pass filtering (0·05–40, 0·1–40, 0·25–40, 0·5–40 Hz), isoelectric levels (TP, PR, M, X), and threshold levels (0·05, 0·10, 0·15). Isoelectric levels: M (mean of TP and PR isoelectric levels), X (single point 40 ms preceding R onset). TH, threshold; DTH, differential threshold; SI, slope intercept; and PSI, peak slope intercept.

23 ms (low pass cut off) for DTH, 37 to 22 ms (low pass cut off) for SI, and 31 to 23 ms (low pass cut off) for PSI.

Discussion

This study compared QT measurements made by different automatic techniques and assessed the influence of lead selection, electrocardiogram filtering, and algorithm parameters. The ranges of mean (SD) of automatic QT difference encountered across the filter and algorithm parameters were large and amounted to a range for the mean$_{AQD}$ of 62 ms and for the SD$_{AQD}$ of 54 (20–74) ms.

Across the different filter/parameter combinations, technique TH demonstrated the largest intra-technique range of mean$_{AQD}$ and SD$_{AQD}$ values. These variations in mean$_{AQD}$, with relatively small changes in filtering and algorithm parameters, coupled with the high values of SD$_{AQD}$, make us unable to recommend the use of technique TH. If technique TH was excluded from the analysis, however, the range of mean automatic QT difference was still 40 ms.

Further analysis of the distribution of automatic QT difference (at standard filter and parameter settings) across all 12 ECG leads revealed differences between the four techniques. The results suggested that measurements were affected by low T wave amplitudes but that no simple relation existed for the range of T wave amplitudes. More importantly perhaps are the inter-technique ranges of mean$_{AQD}$ and SD$_{AQD}$ which would be expected to produce increased dispersion measures relative to the reference. These findings have important implications for automatic QT dispersion measurement.

Our own research[13] has shown a range of 20 ms in mean QT measurements between four independent cardiologists while differences of up to 28 ms have been reported.[8] Mean QT measurements from different automatic techniques are therefore more varied than from a range of expert manual measurers.

Given the small mean difference of 7 ms between the researcher and the cardiologists in the preliminary study, the underestimate of the QT interval by technique SI, relative to the other automatic techniques, might also be expected to apply relative to manual measurements. Such a systematic error can be corrected for if consistent—that is, if the SD of the automatic QT difference is low. In some cases, notably in the measurement of dispersion where absolute QT measurement values are less important than their relative values correction may be unnecessary.

This study has established that with good quality and normal electrocardiograms, techniques DTH, SI, and PSI produce consistent results over most filter/parameter combinations but with an underestimate of the QT interval by SI. Even with these techniques, however, it should be noted that the effect of filtering had a critical influence on their performance. Future work will investigate the influence of noise and pathological T wave morphologies, enabling the performance of these three techniques under more demanding conditions to be established.

In conclusion, QT measurements made from good quality, normal electrocardiograms by automatic techniques can differ considerably. The differences encountered were much greater than between manual measurers. The application of a threshold to the T wave (technique TH), a commonly used automatic QT measurement technique, performed particularly poorly. Furthermore, the non-uniform distribution of automatic QT difference across the different electrocardiogram leads means that dispersion values may be higher for automatically determined QT intervals. Published work must, therefore, describe automatic QT measurement techniques clearly so that any possible influence on the results may be considered. More importantly, QT measurements by any technique, including electrocardiogram machines, using undocumented or proprietary methods must be used with caution, particularly in comparative studies.

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