Enhanced Rhythm Analysis for Resting ECG Using Spectral and Time-domain Techniques

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Abstract

Interpretation of cardiac rhythms is highly dependent on accurate detection of atrial activity. Several new enhancements were made to the previously described MAC-RHYTHM atrial analysis program, including spectral analysis for the detection of atrial flutter; optimal lead selection for P wave detection; and T wave alignment to reduce subtraction artifact in the residual signals used to create a P wave detection function.

Performance was assessed using a test set of 69957 confirmed ECGs from four hospitals. The rhythm interpretation in the confirmed ECG was compared to the rhythm interpretations from the previous and new versions of the program. The rate of disagreements between the confirmed rhythm and the computerized interpretation decreased from 6.9% to 4.1%. Sensitivity improved for sinus, atrial fibrillation, atrial flutter, and junctional rhythms, while specificity and positive predictive value improved for all arrhythmias.

1.   Introduction

Accurate detection of atrial activity is essential for proper cardiac rhythm analysis. Atrial activity manifests itself on the electrocardiogram (ECG) as P waves in the normal ECG, or f or F waves in the case of atrial fibrillation or atrial flutter. The shape and amplitude of the P waves may vary widely from patient to patient, and may be absent altogether in the case of certain rhythms.

Computerized ECG interpretation programs usually perform well for sinus rhythms where there is a 1:1 ratio between the P wave and the QRS complex and a constant PR interval. However, accurate detection of complex atrial arrhythmias, such as second or third degree blocks, remains a difficult task for these programs.

The GE Medical Systems 12SL resting ECG analysis program has undergone continuous improvements since its original release in the Marquette Electronics MAC-2 electrocardiograph in 1982. A new rhythm analysis package, referred to as "MAC RHYTHM", was added to 12SL in 1999 [1-4]. The primary objective of the MAC-RHYTHM processing was to improve sensitivity for P

wave detection in the case of complex atrial arrhythmias. With the increased sensitivity in these rhythms came a small cost in specificity. The focus of the current work was to reclaim the high specificity for very low prevalence rhythms and conversely, increase sensitivity for the higher prevalence rhythms of sinus rhythm and atrial fibrillation, while decreasing the overall population misclassification rate.

2.   Methods and materials

The MAC-RHYTHM processing has been previously described by Reddy et al. [1-4]. The 12SL program uses a non-linear signal averaging method to generate a "median complex", which is a representative beat formed by all beats matching the "dominant" QRS shape. The MAC-RHYTHM processing selects two leads for atrial rhythm analysis (usually II and V1). Each QRS complex is removed by linear interpolation, and the ST-T segment of the median complex is subtracted from each beat of the "dominant" beat morphology after compensating for any baseline shift. The remaining beat's ST-T segments are removed by linear interpolation. After the linear interpolation, but before the ST-T subtraction, the signals are low-pass filtered using a zero-phase filter with a cut-off frequency of 23 Hz. The resulting signals are referred to as the residual signals.

A detection function is then formed by summing the absolute values of the first and second derivatives of the residual signals. The detection function may be expressed as:

$$f[n] = \left| r'_{II}[n] \right| + \left| r''_{II}[n] \right| + \left| r'_{V1}[n] \right| + \left| r''_{V1}[n] \right|$$

where $r'[n]$ and $r''[n]$ are the first and second derivatives of the residual signals of leads II and V1. Detection and delineation of candidate P waves are made from this signal.

Areas of enhancement for the current work include a new spectral method of atrial flutter detection, optimal lead selection for P wave analysis, and improved T wave alignment when subtracting the median complex ST-T segment from the individual rhythm signals.

Two versions of the 12SL program were compared in the present study: versions 18 and 20. Version 18 is the

latest released version of the program containing the original MAC-RHYTHM processing. All of the enhancements described here were implemented in version 19 of 12SL, which was released in January, 2003. As part of our continued development of the analysis program, version 20 has been completed and will be released in new products in 2004. The effects of the changes from versions 19 to 20 are generally unrelated to rhythm interpretation.

The new and previous versions of 12SL were run over a test set of confirmed ECGs and the primary rhythm from the 12SL interpretation was compared to the physician-confirmed primary rhythm stored in the ECG record. Concordance of the primary rhythms was measured and the performance of the two versions of the program was compared.

2.1. New techniques

Atrial flutter detection. In addition to the existing time-domain criteria for atrial flutter, leads II, V1, and V2 are separately analyzed by computing the power spectral density (PSD) after removal of the QRS complexes by linear interpolation and low-pass filtering. The PSD is computed using a 1024 point fast Fourier transform (FFT) after the signal is decimated to 125 samples per second. PSD peaks corresponding to rates of 220 – 400 beats per minute are candidates for atrial flutter. Further analysis of the spectral peaks is used to rule in or rule out atrial flutter.

Because not all ECGs with atrial flutter will have prominent peaks corresponding to a flutter rate, conventional time-domain criteria is also used in order to maintain a high sensitivity.

An example ECG with flutter waves in lead II and the corresponding PSD plot is shown in Figure 1. In this example, significant energy is present in the frequency corresponding to the flutter rate of 334 beats per minute.

Lead selection. The previous version of the program selected leads II and V1 as the preferred leads for atrial analysis. If lead II was considered noisy, lead I was used in its place. Likewise, if lead V1 was noisy, lead V2 was used. While leads II and V1 are often the best leads for atrial analysis in most ECGs, many instances exist where P waves are more evident in other leads.

The new version of the program uses a scoring method to determine the best two leads for atrial analysis. This includes a preliminary search for P waves in either the median complex or the longest RR interval in the rhythm signal for each lead; feature measurement of any detected P waves; and noise measures for each lead. All leads are independently analyzed and the best one of leads I and II and the best one of leads V1 – V6 are selected.

T wave alignment. As described above, 12SL forms a median complex before the MAC-RHYTHM analysis. However, not all beats of the dominant QRS type will
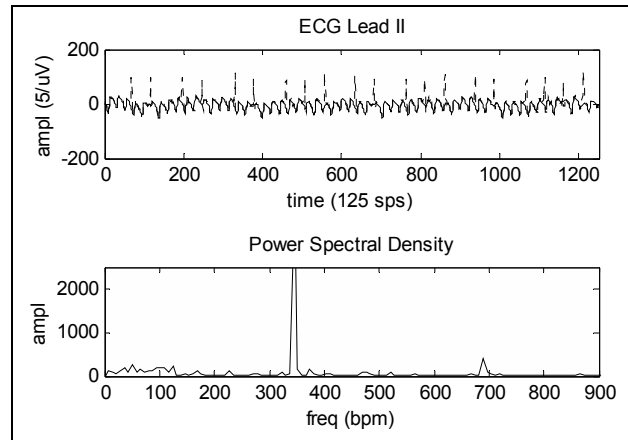

Figure 1. Atrial flutter with variable AV block. Top: lead II. Vertical scale: µV*5 (i.e.,200 = 1000 µV); horizontal scale: sample time at 125 samples per second (10 second trace). Dashed lines are the QRS complexes, which are removed before spectral analysis. Bottom: power spectral density. Note peak at 334 beats per minute. Not all ECGs with flutter show such prominent peaks, and even those that do may have other significant peaks.

have identical T waves, and a straightforward subtraction of the median complex ST-T segment using the detection trigger of the QRS complex as a fiducial point for time-alignment may not always be optimal. Because the amplitude and the duration of T waves may vary with the coupling interval, the selection of a fiducial point within the T wave was found to avoid subtraction artifact in the residual signal that can be mistaken for atrial activity. The new method minimizes the difference between the first derivative of the residual between +/- 40 msec about the peak of the T wave and a straight-line interpolated from the QRS onset to the T offset.

2.2. ECG test set

An ECG database comprising over 70000 randomly selected, physician-confirmed ECG records from four institutions was prepared. Because the ECGs were randomly selected, they may be considered as a representative sampling of ECGs which would be interpreted in clinical practice. Of key importance is that the ECGs used in this study were not used in any way during development.

All ECGs were originally interpreted by earlier versions of the 12SL program at the time of acquisition, and were then confirmed, with our without editing, by a physician.

ECGs with a confirmed rhythm of atrial, ventricular, or AV sequential pacing were excluded from the present analysis. On the other hand, ECGs with a confirmed

rhythm which included "demand" pacing were included in the analysis because 12SL will make an interpretation based on the intrinsic rhythm.

2.3. Analysis

Truth tables were generated based on the confirmed primary rhythm statement in the stored ECG record and the automated interpretation. This step was repeated for the previous and new versions of the program.

From the truth tables, counts of true positive, true negative, false positive, and false negative interpretations were tallied, and sensitivity, specificity, and positive predictive value statistics were computed for each rhythm category. The chi-square test was used to compare differences between proportions.

The primary rhythms were categorized as follows: sinus, ectopic atrial, AV block, atrial fibrillation, atrial flutter, and "No P". Sinus includes all sinus-originating rhythms with 1:1 AV conduction and constant PR interval. Ectopic atrial includes ECGs with unusual P axis, but with 1:1 AV conduction. AV block includes ECGs with 2nd degree AV block (Mobitz I, Mobitz II, or 2 to 1), complete heart block (i.e., 3rd degree AV block), or AV dissociation. The "No P" category refers to rhythms in which P waves are not present or not observed, including junctional rhythm, wide QRS rhythm, idiopathic ventricular rhythm, and supraventricular tachycardia (SVT).

ECGs with a confirmed rhythm of "Undetermined Rhythm" were listed in the truth tables, but excluded from the tabulations. Likewise, ECGs for which 12SL gave a rhythm interpretation of "Undetermined Rhythm" were listed in the truth tables, but excluded from the tabulations (for that version of 12SL). That is, an interpretation of "Undetermined Rhythm" was considered neither right or wrong.

3. Results

Overall results are tabulated in Table 1 and the sensitivity and positive predictive value results are graphed in Figures 2 and 3.

A total of 74313 ECGs were processed. Several ECGs were excluded for the following reasons: the "confirmed" flag was not set in the stored record (660); the confirmed rhythm interpretation was paced (atrial, ventricular, or AV sequential) (635); no confirmed primary rhythm statement remained in the record after editing (2482). Another 579 ECGs contained the "Undetermined rhythm" statement as the primary rhythm in the confirmed interpretation. This left 69957 ECGs remaining for the analysis, which is the sum of the "N" row in Table 1.

The overall discordance rate is the number of ECGs where the primary rhythm of the computerized interpretation differed from the primary rhythm in the stored confirmed ECG record out of the 69957 ECGs referred to above, excluding those ECGs where the computerized interpretation was "Undetermined rhythm". The discordance rates are summarized in Table 2. The discordance rate decreased from 6.9% in the previous version to 4.1% in the new version (p < 0.001).

Table 1. Performance statistics for old and new versions of 12SL. EAR: ectopic atrial rhythm; AVB: 2nd or 3rd degree AV block; AFL: atrial flutter; AFIB: atrial fibrillation; NoP: rhythms without P waves (junctional, supraventricular tachycardia, etc.); N: total number of ECGs with this confirmed rhythm; Sens: sensitivity; Spec: specificity; PPV: positive predictive value; §: significant change (p < 0.01).

	Sinus	EAR	AVB	AFL	AFIB	NoP
N	62397	1066	120	576	5163	635
V18						
Sens	95.7	56.9	56.8	51.2	79.7	46.3
Spec	87.5	98.4	99.1	99.4	99.0	98.4
PPV	98.5	34.9	9.5	42.4	86.1	20.9
V20						
Sens	98.2 §	35.2 §	49.1	55.0	89.0 §	63.1 §
Spec	85.5 §	99.7 §	99.6 §	99.6 §	99.4 §	99.1 §
PPV	98.3 §	63.4 §	18.1 §	50.7 §	91.9 §	38.1 §

Table 2. Overall discordance rates.

Version	Discordance rate
V18	6.9 %
V20	4.1 %

4. Discussion

The primary objective of the present development work was to increase the sensitivity for sinus rhythms and to increase the specificity for the lower-prevalence arrhythmias. Based on feedback from users, the previous version was found to be too sensitive to ectopic atrial rhythm and second degree AV blocks. In addition, we found that the program was erroneously stating junctional rhythms when P waves were not evident in leads II or V1, but evident in other leads. The changes made to the program address these issues.
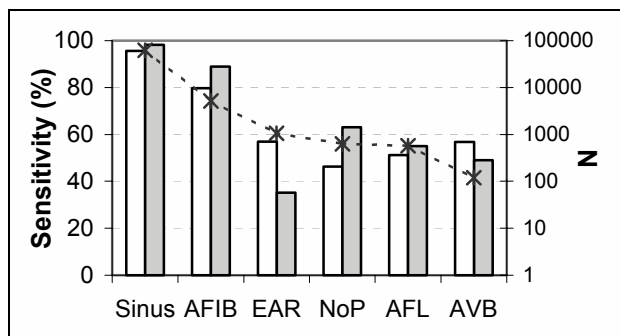
Figure 2. Sensitivity of each rhythm classification for both versions of 12SL. White bars are V18; dark bars are V20; asterisks and dashed line are counts (N), corresponding to logarithmic scale on right.
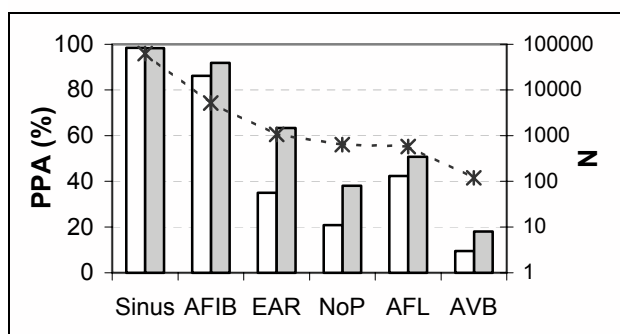

Figure 3. Positive predictive accuracy of each rhythm classification for both versions of 12SL. Refer to Figure 2 for legend.

The results show increases in sensitivity for sinus, atrial fibrillation, atrial flutter, and "No P" (mostly junctional) rhythms. Decreases in sensitivity were observed in ectopic atrial and AV block (non 1:1 conduction) rhythms. These decreases were in line with design decisions. More importantly, the specificity and the positive predictive accuracy increased for all of the arrhythmia categories (ectopic atrial, atrial fibrillation, atrial flutter, "No P", and AV block).

Although a trade-off in sensitivity for ectopic atrial and AV block rhythms was made, this is in part justified by the overall improvement in the program over the entire population. The overall discordance rate between the confirmed interpretation and the computerized interpretation dropped from 6.9% to 4.1%, reflecting better agreement with the physician.

A limitation of this study is the assumption that the rhythm statement in the confirmed ECG was the true rhythm. It is known, however, that this is not always the case. The accuracy of the interpretation in the confirmed ECG depends largely on the overreading physician. Often the physician may not wish to spend time correcting the original 12SL interpretation for statements that may seem marginal or irrelevant to patient care.

Different institutions may have varying quality control procedures regarding the process of confirming the ECG, or there may be an institutional bias in overreading. Selecting ECGs randomly from four institutions was the best way to mitigate this limitation.

Another limitation, somewhat related to the first, is the extent to which the overreading physician may be influenced by the original 12SL interpretation.

The strength of this study is the large number of ECGs analyzed, as well as the fact that the database provided a representative sampling of the ECGs that 12SL is faced with on a daily basis. Because the ECGs used in this analysis are a representative sampling drawn from four institutions, the values reported here will be reflective of the performance in actual clinical practice.

As a separate validation of the changes described here, we worked with three US institutions to assess the improvements to the program. Version 19 of 12SL was installed on all GE MAC 5000 electrocardiographs at the three sites. After using the new software for at least 30 days, database searches were conducted on their MUSE ECG storage systems to assess the percentage of ECGs which required any editing of the interpretation for the 30 days prior to the software upgrade and the 30 days following the upgrade. All three institutions showed significant reductions in the percentage of edited ECG interpretations.

References

[1] Reddy BRS, Elko PP, Christenson DW, Rowlandson GI. Detection of P waves in resting ECG: A preliminary study. Computers in Cardiology 1992. Los Alamitos, CA: IEEE Computer Society Press, 1992:87-90.

[2] Reddy BRS, Elko PP, Christenson DW, Rowlandson GI. Detection of complex atrial arrhythmias in resting ECG. Computers in Cardiology 1994. Los Alamitos, CA: IEEE Computer Society Press, 1994:777-780.

[3] Reddy S, Elko P, Swiryn S. A new arrhythmia anlaysis program, MAC-RHYTHM, for resting ECG. In: Liebman J, editor. Proceedings of the XXIII International Congress on Electrocardiology 1996. Singapore: World Scientific, 1996:471-480.

[4] Reddy BRS, Taha B, Swiryn S, Silberman R, Childers R. Prospective evaluation of a microprocessor-assisted cardiac rhythm algorithm: Results from one clinical center. J. Electrocardiology 1998 vol. 30 supplement, 28-33.

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