Journal of Medical Imaging and Health Informatics
Vol. 4, 1–6, 2014

A Study on Atrial Ta Wave Morphology in Healthy Subjects: An Approach Using P Wave Signal-Averaging Method

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Introduction: Filtered and unfiltered signal-averaged P wave analyses are in existence for the detailed study on the P wave morphology. Information on the atrial repolarization (Ta wave) is seldom explained. *Objective*: In the present study, Modified Limb Lead (MLL) ECGs were recorded and studied using unfiltered signal-averaged P wave analysis to better describe the atrial P and Ta wave morphology. In addition, a novel algorithm is proposed for the R wave peak detection from the recorded MLL ECG. *Methods*: Sixty healthy male subjects (mean age 39 years) were included in this study. MLL ECGs were recorded with BIOKIT INDIA ECG (3-lead) system and EDAN SE-1010 PC ECG system. Unfiltered signal-averaged P wave analysis was used to investigate the measured P and Ta wave peak amplitude and duration. *Results*: The average P wave duration was 91 ± 2.6 ms. The observable Ta wave duration was 109 ± 4.7 ms, the P-Ta interval was 198 ± 2.9 ms and the corrected P-Ta interval was 241 ± 4.7 ms. The P wave and the Ta wave amplitude was 117 ± 23 μV and 43 ± 12 μV respectively. The Ta wave maxima was located at 150 ± 5.7 ms. Significant correlation was found between the values of P wave and Ta wave amplitude ($r = 0.30$, $P = 0.01$). *Conclusion*: The Ta wave was clearly observed in the healthy subjects using the MLL system with better beat averaging. The Ta wave was opposite in polarity to the P wave and longer in duration. The Ta wave maxima are generally located in the PR interval during normal AV conduction. The P and Ta wave duration was altered due to increase in age. The P-Ta interval shortened with increasing heart rate. The proposed algorithm showed excellent *P* and *R* peak detection.

Keywords: Modified Limb Lead, P Wave, QRS Complex, Signal Averaging, Ta Wave.

1. INTRODUCTION

Abnormal ventricular repolarization in ECG is the key marker for different types of ventricular arrthymia. Changes in the QT interval reveals about the cardiac chamber hypertrophy and changes in the ST segment indicate cardiac ischemia and myocardial infarction which leads to sudden death.[1,2] The electrocardiographic deflection of the atrial repolarization (Ta wave) is small in amplitude and area, compared to the QRS complex. Generally the Ta wave is obscured by the QRS complex in healthy subjects. In conditions where AV block is present, the Ta wave is noticed and recorded in the standard ECG.[3–5]

The electro physiological changes during atrial arrthymia are well explained in several previous studies.[6–8] Atrial refractory period tends to shorten as the atrial arrthymia sustain, which is likely to have an influence on atrial repolarization phase. The properties of atrial repolarization might give rise to atrial arrhythmias in the same way as ventricular repolarization relates to ventricular arrhythmia.[1] It is therefore important to determine the normal atrial P wave, Ta wave and P-Ta interval which may lead to more information about the atrial arrhythmias. Changes in heart rate may result in alterations of the P-Ta interval duration and morphology. Better delineation of atrial Ta waves will help us to decode the mysteries surrounding the atrial repolarization.

Langley and Murray done a preliminary study on atrial repolarization phase using signal averaging method in normal sinus rhythm with small group ($n = 10$) of healthy and paroxysmal atrial fibrillation (PAF) subjects.[9] In that study, analysis of the short Ta wave segment visible during normal AV conduction did not reveal any differences between subjects with a history of atrial fibrillation and those without.[9] Holmqvist et al. studied the presence of atrial Ta wave in AV block patients transformed to orthogonal lead using inverse Dower transform and performed signal-averaged P wave analysis.[10]

Sivaraman et al. recently proposed a modification in the placement of limb electrodes of the 12 lead ECG for the enhancement

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of P waves and described the normal amplitudes and frontal plane axis of the new MLL system.[11] In other study, Sivaraman et al. described the impact of atrial Ta wave in healthy subjects and in AV block patients using the MLL system.[12] Studies on signal-averaged analysis on P wave morphology during sinus rhythm are in detail.[13–17] Studies done on atrial Ta wave in healthy subjects using signal averaged atrial beat are scarce. Preliminary investigation done by Langley and Murray studied only a small part of the atrial repolarization phase of the ECG in healthy subjects.

In general, heart rate variability (HRV) is studied using *R–R* interval which require the detection of *R* peaks in the ECG waveform. Several signal processing techniques based on higher order spectra (HOS), power spectral analysis, weight factor mode (WFN), heart instantaneous frequency (HIF) are in existence for the study of heart rate variability. Automated *R* peak detection methods based on the derivatives,[18] and digital filters[19–23] were unable to distinguish between the *P* and *R* peak of the MLL system.

In the present study, the unfiltered signal-averaged P wave analysis was investigated in the healthy subjects recorded by the MLL system to better delineate the P and Ta wave morphology. A novel *R* peak detection algorithm was proposed based on template matching with adaptive threshold to better detect the *P* and *R* peak in the modified limb lead system.

2. METHODS

2.1. Subject Population

ECG data from 60 healthy male subjects of mean age 38.85 ± 8.76 (SD) in the range of 25 and 58 years was used to investigate the methodological effects on the P and Ta wave duration and morphological parameters. The same data set was also used to evaluate the P and R wave detection algorithm. The 12-lead ECG recorded on healthy male subjects revealed no trace of cardiac disorders. No hypertensives were included in the recording. Smokers and other patients with congestive heart failure, valvular disease, atrial fibrillation and other cardiopulmonary diseases which may alter the ECG morphology are excluded from this study. This study was approved by the institute ethics committee and all the subjects were given consent before data recording.

2.2. Data Acquisition and Analysis

Modified limb lead ECG[11] from healthy male subjects in supine position was recorded for 60 seconds duration. ECGs were sampled at 500 Hz with an amplitude resolution of less than 50 μV. The ECG data were transferred to a computer and stored for subsequent off-line processing. The digital data analysis of ECGs was performed using MATLAB for Windows. Figure 1 illustrates the processing steps used in the measurement of atrial P and Ta wave amplitude and process flow of *R*-peak detection in the modified limb lead system.

The observable portion of the Ta wave is small in amplitude and beat averaging is necessary to obtain signals with good signal to noise ratio. Multiple atrial beats were time aligned and only beats over a threshold were used to generate the average atrial beat in each lead.[9] Amplitudes of the atrial P and Ta wave were measured manually and relative to zero isoelectric level. The location and amplitude of the Ta peak was determined manually

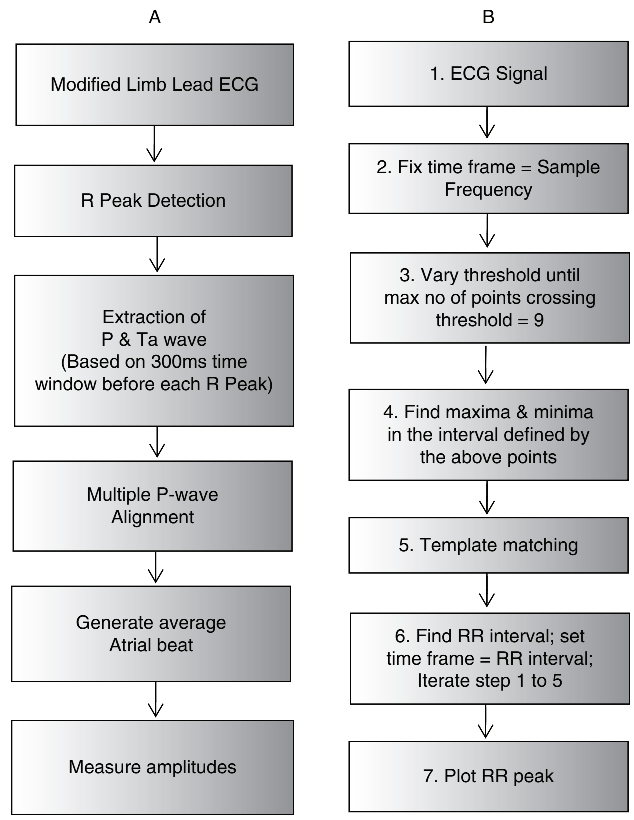

Fig. 1. (A) Processing steps for generating average atrial beats and amplitude measurements. (B) Process flow of *R*-peak detection algorithm for the modified limb lead system.

in each lead. The onset and end of the P wave and the observable Ta wave were set and measured manually.

2.3. Algorithm Overview

The individual cardiac beats in the entire recording were identified by a *R* peak detector. The *R* peak detection algorithm is based on pre-set template matching technique with adaptive threshold method, which changes the threshold level at the end of the each iteration. This method involves by varying the threshold level, such that a fixed number of points cross the threshold band for a given time frame. A time window is fixed which is same as the sampling frequency of the ECG signal, within which it tries to find the threshold.

The threshold value is iteratively incremented until the required number of maxima and minima lies within the threshold points. Then, an appropriate local maxima and minima within each interval are defined by the above points. The *R–R* interval can be found out from the detected *R* peaks and can be used to set a new time frame such that only one ECG cycle is accommodated. With this time frame the whole process is reiterated for improving the sensitivity of the algorithm.

Once the *R* peak is detected, the next step is to define a window containing the atrial P and the observable Ta wave in the atrial beat. For each modified limb lead ECG the window covered an interval of 300 ms before the R wave peak in each beat. The window was adjusted manually to ensure that the window contained no ventricular activity. The window could be manually redefined if necessary. The data window was time-shifted and the P waves were merged and averaged.

Generally in the standard 12-lead ECG the *R* peak amplitude is greater than the *P* peak amplitude which makes any template matching algorithm to detect the QRS peak without any constraint. But in the case of the MLL ECG, the virtue of the MLL system reduces the *R* peak amplitude, enhances the *P* peak amplitude and records the Ta wave compared to the standard 12-lead ECG system. Moreover the Ta wave is not observed and recorded in the standard 12-lead ECG in any of the previous studies done on healthy subjects. This phenomenon makes any existing template matching algorithm and several other algorithms to fail in detecting the *R* peak in the MLL ECGs, where most of the *R* peak amplitudes are similar to the *P* peak amplitudes and the Ta wave is significant in this study. To overcome this limitation in the existing algorithms, the authors propose a template matching algorithm which accounts for the MLL ECG template which includes the Ta wave and it is of first kind in detecting the *R* peak and *P* peak from the MLL ECG traces.

2.4. Definitions

The end of the P wave (and the beginning of the Ta wave) was arbitrarily defined as the point at which the ECG trace crossed the isoelectric line.[24] The P wave duration (PWD [ms]) was defined as the difference in time between the P wave onset and end.[13] The observable Ta wave duration (TaWD [ms]) was defined as the difference in time between the Ta wave onset and the observable end. The interval from the beginning of the P wave to the observable Ta wave end was defined as the P-Ta Interval. The P wave end to the observable Ta wave end was defined as the Ta duration.[12]

2.5. Statistical Analysis

All data are expressed as the mean ± standard deviation. The Shapiro-Wilk *W* test was used for testing the normality and all the data were normally distributed. Pearson correlation was used for correlation analyses. All tests were two-sided and value $P <$ 0.05 was considered statistically significant. The collected data were statistically evaluated using Win STAT in Excel for Windows (Microsoft Office 2010).

3. RESULTS

The mean amplitude and duration measurements of the P wave and the Ta wave recorded by the MLL system using unfiltered signal-averaged P wave analysis are shown in Figure 2. The data were found to be statistically significant (Student *t*-test, $P < 0.05$) for both the atrial P wave and Ta wave amplitude and duration. The Ta wave morphology and its relation to the P wave morphology obtained using unfiltered signal-averaged P wave analysis clearly depicts the locations and the amplitudes of the *P* peak and Ta peak maxima as shown in Figure 3. The average atrial beats of five healthy male subjects without and with beat alignments are shown in the Figure 4. The average P wave duration was 91 ± 2.6 ms. The observable Ta wave segment was 109 ± 4.7 ms and the total P-Ta interval was 198 ± 2.9 ms. The average atrial rate was 73 ± 6.7 bpm and the corrected P-Ta interval was 241 ± 4.7 ms.[24]

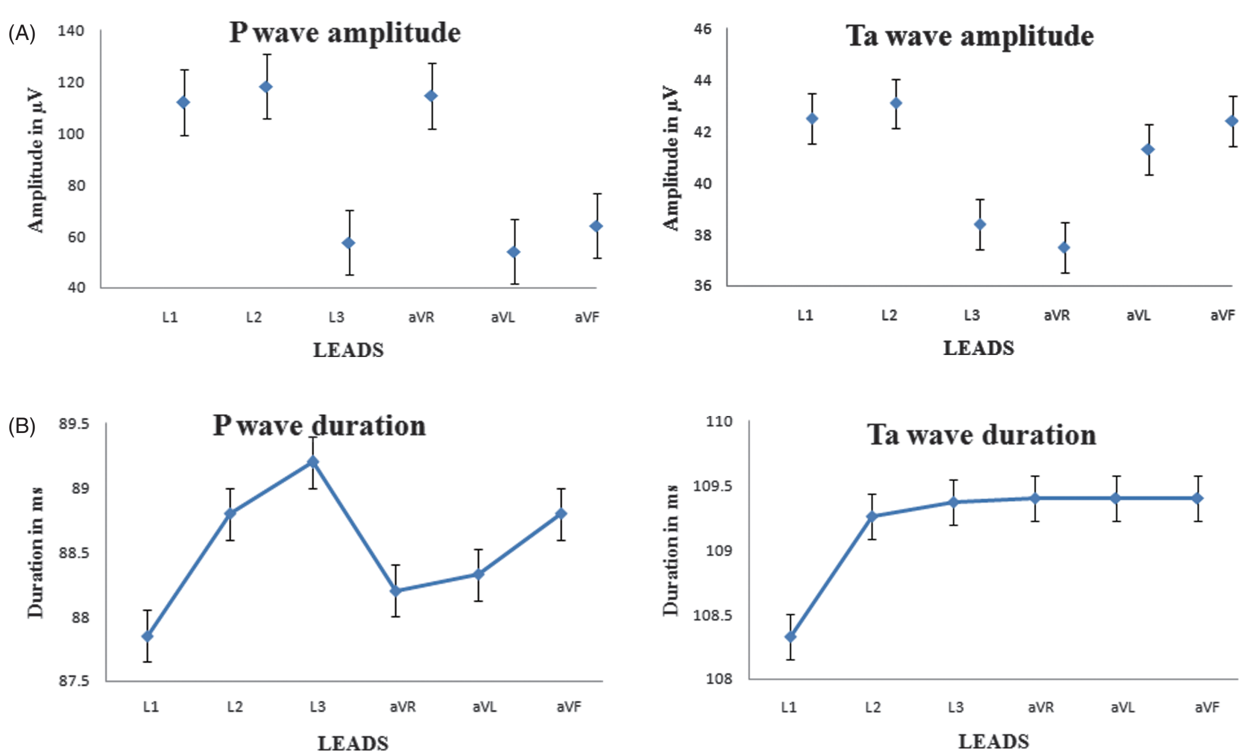

Fig. 2. (A) Plots of Mean ± SE of P wave and Ta wave amplitudes (B) plots of Mean ± SE of P wave and the observable Ta wave durations in the modified limb electrode positioning placed in the torso of the subjects. *Y*-axis units are in micro volts and milliseconds respectively. Note the different *Y*-axis scales between the plots of each row.

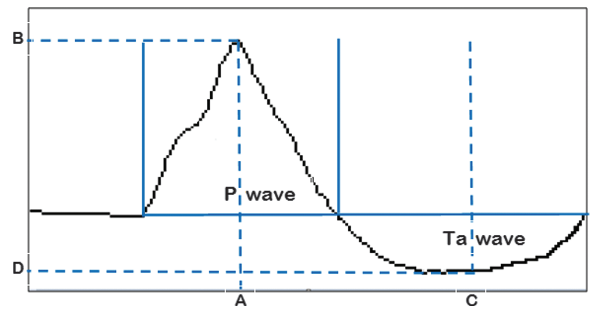

Fig. 3. Schematic illustration of the P and Ta wave parameters derived from the unfiltered signal-averaged P wave morphologies. Location (A) and amplitude (B) of P wave maxima; location (C) and amplitude (D) of Ta wave maxima.

The histograms illustrating the distributions of the P-Ta interval duration and the observable Ta wave duration are shown in Figure 5. The P-Ta interval duration and the Ta wave duration were found to be normally distributed with $P = 0.93$, $P = 0.67$ respectively (Shapiro-Wilk W-test). The P wave and the Ta wave peak amplitude were 117 ± 33 μV and 43 ± 12 μV respectively. Significant correlation was found between the values of the P wave amplitude and the Ta wave amplitude ($r = 0.30$, $P = 0.01$). No correlation was found between the P wave and the Ta wave duration ($r = -0.14$, P = NS) or between the Ta peak amplitude and the Ta wave duration in any of the signals analyzed ($r = -0.18$, P = NS).

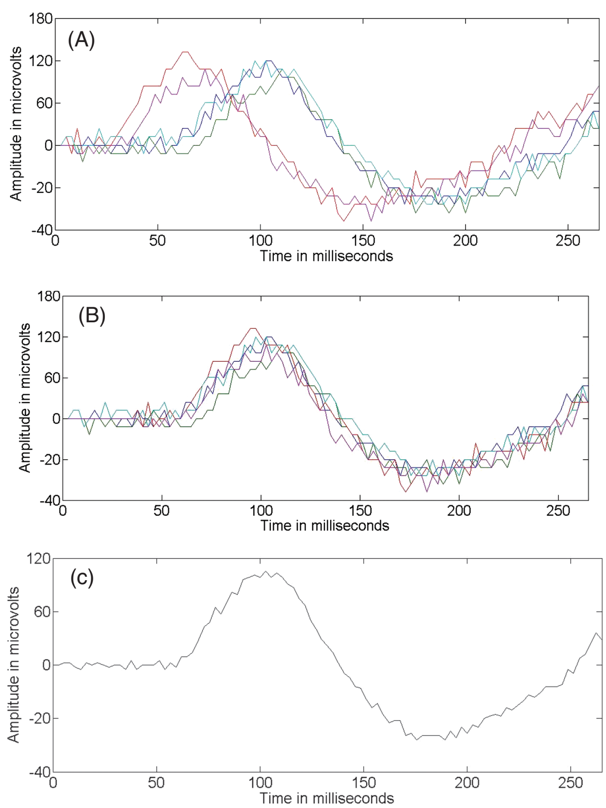

Fig. 4. Atrial beat of 5 healthy male subjects. Amplitude is shown in μV, time duration in ms. (A) Atrial Beat without beat alignment, (B) atrial beat with beat alignment and (C) average atrial beat. (Note the different Y-axis scale.)

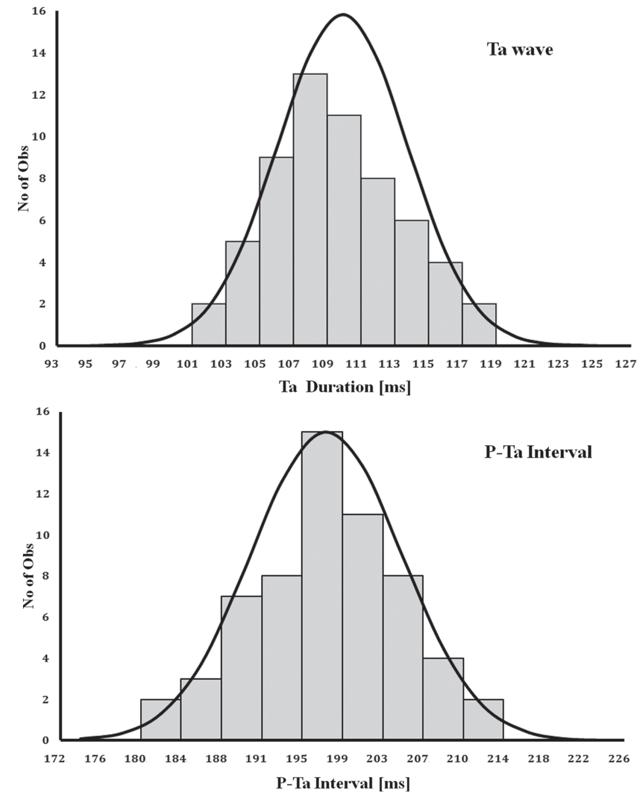

Fig. 5. Histogram illustrating the distributions of Ta wave duration and P-Ta interval. The distributions are not significantly different from the normal distributions ($P = 0.93$ and $P = 0.67$, respectively, Shapiro-Wilk W-test.)

Regarding the R wave detection algorithm the sensitivity and the specificity of the developed algorithm was evaluated using the modified limb lead ECG data set. The algorithm was implemented on the MLL ECG and was able to detect consistently the R wave peak amplitude as shown in the Figure 6. In addition to the R peak detection, the algorithm was also modified to detect the P peak of the MLL ECG trace for the measurement of the P-P interval as shown in Figure 6.

4. DISCUSSION

In the present study the observable Ta wave in the healthy subjects was found to be substantially longer than the P wave and of opposite polarity in all the leads which was analyzed. This is in agreement with the findings in similar previous study done on the healthy subjects by Langley and Murray[9] and in several previous studies done on AV block patients.[3–5, 10] The finding of

Table I. Measured parameters of P wave and Ta wave morphology.

Measurements		Values
Atrial rate	bpm	74 ± 06
P wave duration	ms	91 ± 2.6
Ta wave duration	ms	109 ± 4.7
P-Ta interval	ms	198 ± 2.9
Corrected P-Ta interval	ms	241 ± 4.7
Ta peak amplitude	μV	43 ± 12
Ta peak location	ms	150 ± 5.7
P wave amplitude	μV	117 ± 23

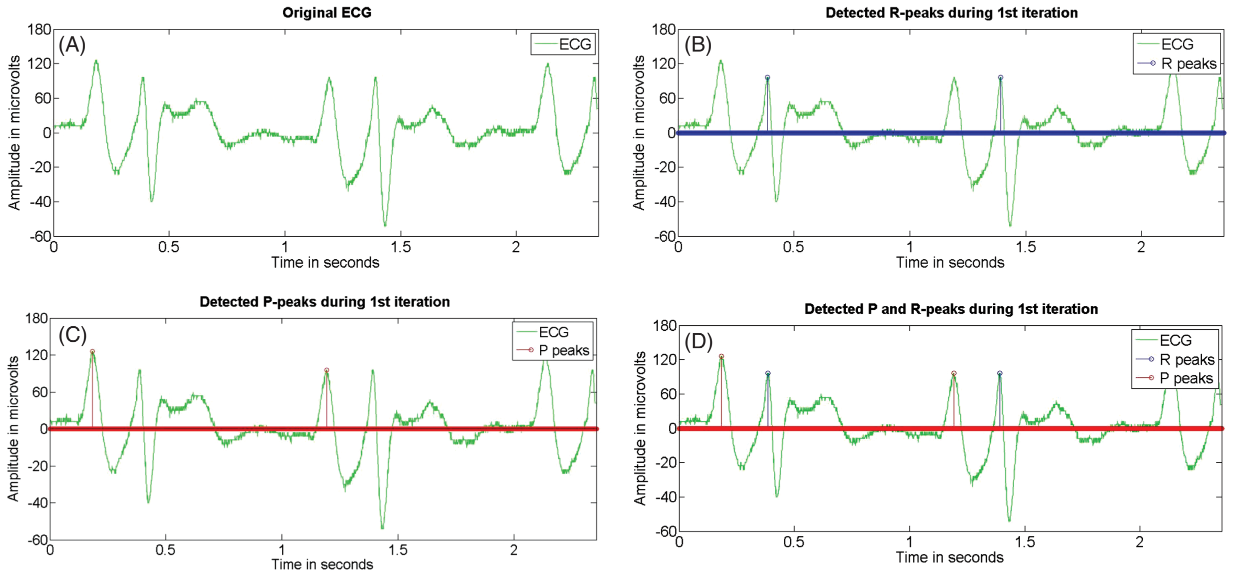

Fig. 6. (A) Detection of *R* and *P* peaks from the MLL system using template matching with adaptive threshold techniques. Amplitude is shown in mV, time duration in seconds. (A) Original ECG signal, (B) detection of *R* peak, (C) detection *P* peak (D) detection of both *R* and *P* peak using the algorithm.

the opposite polarity of the P wave and the Ta wave is in contrast to the case of the QRS complex and the T wave.[25]

Langley and Murray in their preliminary study were able to analyze only a small part of the atrial repolarization phase using signal-averaged P wave analysis on the standard 12-lead ECG and found that the mean P wave and the Ta wave amplitude to be 100 μV and 15 μV respectively. In the present study the mean P wave and Ta wave amplitude was found to be 117 μV and 43 μV respectively. The difference in the mean amplitudes of the P wave and the Ta wave in healthy subjects compared with the preliminary results by Langley and Murray is generally due to the modified limb lead system used in recording the ECGs in the present study.

Signal-averaged ECG studies on atrial repolarization phase are scarce, but the results of the study by Langley and Murray did not document or reveal any alterations or variations in the Ta wave duration or the observable P-Ta interval in healthy and Paroxysmal atrial fibrillation (PAF) patients.[9] Based on the findings in the present study, the Ta wave and P-Ta interval duration did alter to some extent due to increasing age.

Holmqvist et al. described the Ta wave using unfiltered signal-averaged P wave analysis and mentioned that the Ta wave maxima may occasionally be located in the PQ interval during normal AV conduction.[10] In the present study, the occurrence of the Ta wave maxima was noticed well over 150 ms after the onset of the P wave in the PQ segment which is well within the PQ interval. With the normal PQ interval generally being below 200 ms, this implies that the Ta maxima are located in the PQ segment during normal AV conduction.

Havmoller et al. described the age related changes in the P wave morphologies using signal-averaged P wave analysis of the healthy subjects.[15] It is manifest that similar changes would alter or prolong the Ta wave morphology in healthy subjects. This was evident and in agreement with our present study that increasing age was a factor for the prolongation of the P wave and the Ta wave.

Debbas et al. described the dynamics of the Ta wave in heart block patients and were able to find a shortening of the P-Ta interval as the heart rate increased during pacing.[24] In the present study, the increase in the heart rate altered the observable P-Ta interval in the healthy subjects which is in agreement with earlier study done by Debbas et al.[24] and Holmqvist et al.[10]

Since the unfiltered signal-averaged P wave analysis was performed only on healthy subjects pathologically long or short Ta wave duration or P-Ta interval are not seen in the present findings.

A preliminary qualitative analysis has revealed that the algorithm was able to consistently and accurately detect the *R* peak and *P* peak from the modified limb lead ECG signals that could vary between subjects and also over the time of data collection.

5. STUDY LIMITATIONS

The unfiltered signal-averaged P wave analysis method is well established for the detail analysis of P wave morphology.[13–15] The extension of the method to enable the analysis of the Ta wave in healthy subjects is unlikely to affect the validity of the method. The Ta wave minima were unobservable in this study as the later part of the repolarization phase is hardly seen in the healthy subjects. Of course we had not studied the later part of the atrial repolarization phase and it may be that the abnormalities are manifest in the unobservable later stages of the repolarization. The *R* peak detection algorithm is valid only for the healthy subjects in resting supine position.

6. CONCLUSION

Generally the presence of AV block was a prerequisite for the analysis of the Ta wave in most studies except one preliminary study done by Langley and Murray. In the present study unfiltered signal-averaged P wave analysis was performed on the modified limb lead ECG traces for better delineation of the P wave and Ta wave. The Ta wave was found to have opposite polarity to the P wave regardless of which lead was analyzed. The Ta wave maxima are generally located in the PQ interval during normal AV conduction.

Regarding the P wave and Ta wave duration morphology, the PWD and TaWD did alter to some extent as the study population comprised of different age groups. The Ta wave duration is generally longer than the P wave duration. Obviously, future larger studies are needed to differentiate normal from abnormal atrial repolarization. The *R* peak detection algorithm was able to locate the *P* and *R* peak accurately in the each lead of the MLL system.

Acknowledgments: The authors would like to acknowledge the support from the MHRD, Government of India. This research work was carried out in Madras Medical College, Rajiv Gandhi Government General Hospital, Chennai. None of the authors has any conflict of interest to declare.

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Received: 9 December 2013. Revised/Accepted: 17 March 2014.