Unmasking of atrial repolarization waves using a simple modified limb lead system

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Abstract

Objective: In the present study, a modified limb lead (MLL) system was used to record the Ta wave in sinus rhythm and with AV block in male patients.

Methods: Eighty male subjects (mean age 36±7 years) in sinus rhythm and 20 male patients with AV block (mean age 72±5 years) were included in this study. Standard limb lead (SLL) ECGs and MLL ECGs were recorded for 60 seconds each with an EDAN SE-1010 PC ECG system.

Results: In sinus rhythm subjects, the observable Ta wave duration was 109±4.7 ms, the P-Ta duration was 196±5.1 ms, and the corrected P-Ta duration was 238±7.2 ms. The Ta wave peak amplitude was -42±8 μV. In AV block patients, the Ta wave duration was 314±28 ms the P-Ta duration was 418±29 ms and the corrected P-Ta duration was 462±31 ms, while the Ta wave peak amplitude was -37±9 μV. A correlation was found between the P and Ta wave amplitude, and no correlation was found between the P and Ta wave duration or the Ta amplitude and Ta duration in sinus rhythm and AV block subjects.

Conclusion: The end of the Ta wave is not observable in sinus rhythm subjects, as it extends into the QRS complex and ST segment. In AV block patients, the Ta wave duration was generally three times longer than the observable Ta duration in sinus rhythm subjects.

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Keywords: atrial Ta wave, AV block, modified limb lead system, PR segment, standard 12-lead ECG

Introduction

Human atrial depolarization is represented by the P wave and it is well observed and recorded by the standard 12-lead ECG in sinus rhythm subjects. As the human Ta wave of atrial repolarization occurs during the PR segment and QRS complex, it is not observed and recorded widely in sinus rhythm subjects by the standard 12-lead ECG (1). This is generally due to the amplitude being very low, usually in the range of 10-60 μV, and also, ventricular activation normally begins before atrial repolarization ends, and therefore, the QRS complex overlaps with the Ta wave. However, during second and third-degree AV block, a QRS complex may not follow every P wave or may be dissociated from the P wave, which leads to the visualization of the complete Ta wave.

Sprague et al. (2) first described the Ta wave in third-degree AV block patients and noted that the Ta wave polarity was opposite and that the duration was longer than in the P wave. Other earlier studies (3-7) described the presence of the Ta wave in the PR segment during heart block, in agreement with the initial study of Sprague and White. The signal-averaged P wave analysis method for the study of P wave morphology and interatrial conduction has been explained in detail (8-10).

Langley et al. (11) described the presence of Ta wave in healthy subjects (n=5) by the standard 12-lead ECG using a signal-averaged P wave analysis method. Ihara et al. (12) described the presence of atrial repolarization in healthy subjects (n=75) during the PQ interval using a 64-lead body surface potential mapping system and XYZ signals of the vector cardiogram (VCG). Kozlikova et al. (13) described the opposite polarity of the PQ segment compared to the P wave in healthy subjects (n=26) and in other abnormal subjects using the 24-lead system, from which isointegral maps were derived. Debbas et al. (14) studied the effects of the sinus rate, pacing, and drugs on the Ta wave in heart block patients. Wang et al. (15) described the imaging of atrial repolarization patterns in a healthy subject (n=1) using a

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256-carbon electrode mapping approach supplemented by an inverse model (electrocardiographic imaging, ECGI).

The clinical significance of the precordial chest leads placed on the human torso for studying the electrical activity of the left and right ventricles is well established (16, 17). Few lead systems placed on the human torso have been designed for recording and studying the electrical activity of the atria (18). Much more information about the Ta wave is essential during normal AV conduction to differentiate the normal and abnormal Ta wave (7). The clinical significance and alterations of the Ta wave and the P-Ta segment in atrial arrhythmias have been discussed by Childers (19) and Henry et al. (20).

Sivaraman et al. (21) recently proposed a modified limb lead (MLL) system for unmasking the atrial Ta wave in sinus rhythm subjects and in AV block patients. Using the MLL system, the same authors reported on the normal limits of the P wave amplitudes and frontal plane P wave axis (22) and also studied the P and Ta wave morphology in healthy subjects using the P wave signal averaging method (23). Some form of separation of the atrial and ventricular ECG components is needed to shed light on the Ta wave during sinus rhythm and in atrial arrhythmias.

In general, the Ta wave has not been observed or recorded during the PR segment in healthy subjects using ECG studies. The present study aims to record the Ta wave in healthy subjects during sinus rhythm using the MLL system (21). The MLL system is used to record the ECGs from sinus rhythm subjects and from patients with different forms of AV block in order to study the characteristics of the atrial Ta wave.

Methods

Subjects

Eighty male subjects of mean age 36±7 years (range 25-58 years) in sinus rhythm and 20 male patients with a variety of forms of AV block and mean age 72±5 years (range 62-75 years) were included in this study (Table 1). All volunteers in sinus rhythm were recruited into the study from the outpatient department of the Rajiv Gandhi Government General Hospital, Chennai India, and all were medically examined to exclude any form of cardiovascular disease. Non-hypertensive subjects were included in the study. Smokers and patients with congestive heart failure, valvular disease, atrial fibrillation, and other cardiopulmonary diseases that may alter the ECG morphology were excluded from this study, which was approved by the institutional Ethics Committee. Patients with a variety of forms of AV block were also recruited from Rajiv Gandhi Government General Hospital, Chennai. Each was admitted for up to 1 week while awaiting implantation of a permanent cardiac pacemaker system. All subjects gave informed consent for participation in the study.

Modified limb electrode placement

The modified limb electrode placement (22) of the MLL system is briefly described as follows (Fig. 1). The right arm electrode is placed on the subject's third right intercostal space, slightly to the left of the mid-clavicular line. The left arm electrode is placed in the 5th right intercostal space, slightly to the right of the mid-clavicular line, and the left leg electrode is placed in the 5th right intercostal space, on the mid-clavicular line. The right leg electrode is placed on the subject's right ankle. The polarity of the right arm electrode is negative, and the polarity of the left arm and left leg electrode is positive. The usual terminology applies-e.g., the potential difference between the right arm electrode (RA) and left arm electrode (LA) is still denoted as lead I, etc. The standard precordial electrode positions V_1-V_6 are unchanged in this study during the MLL recordings, but they have no role to play in this study.

Table 1. Basic statistics of the age of the subjects studied

	Age statistics	
Healthy subjects	80 (36±7)	(25.0, 37.5, 58.0)
AV block patients	20 (72±5)	(62.0, 67.0, 75.0)
All subjects	100 (41±11)	(25.0, 37.0, 75.0)
Values are presented as n (mean±SD) (minimum, median and maximum)		

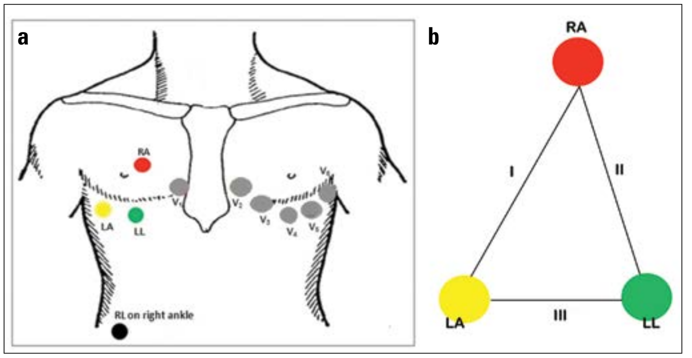

Figure 1. a, b. (a) Placement of limb electrodes on the torso. The precordial electrodes are unchanged. (b) Modified limb lead system

Data acquisition and analysis

Standard 12-lead and MLL ECGs were recorded in the supine position using surface Ag-AgCl electrodes and a digital electrocardiograph (EDAN SE-1010 PC ECG system, EDAN Instruments, Inc., China), operating at 1000 samples per second with a frequency response of 0.05 Hz to 150 Hz. ECGs could be printed at a variable gain from 2.5 mm/mV to 100 mm/mV and a variable paper speed of 5 mm/s to 200 mm/s. The standard 12-lead ECG and the MLL ECG were recorded for 60 seconds at a standard ECG paper speed of 25 mm/s and 10 mm/mV and analyzed separately for comparative purposes.

In the MLL ECG trace, the onset and termination of the P wave and the observable Ta wave in the PR interval were measured manually. The end of the P wave (and the beginning of the observable Ta wave) was arbitrarily defined as the point at which the waveform returned to the level of P onset (14). The interval from the P wave onset to the observable Ta wave end was defined as the P-Ta Interval. The interval from the P wave end to the observable Ta wave end was defined as the Ta duration. A corrected P-Ta interval (14) was obtained using the fol-

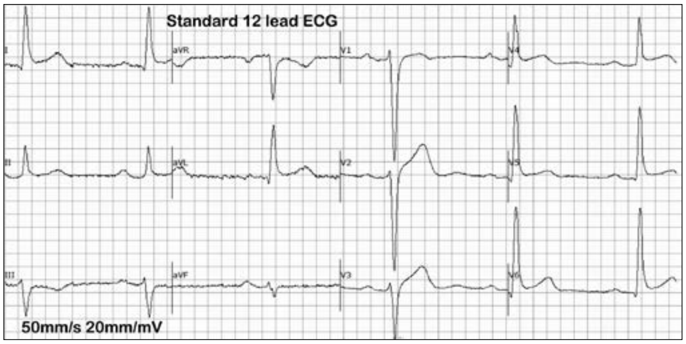

Figure 2. Standard 12-lead ECG of a 32-year-old male subject in sinus rhythm. The ECG paper scale is adjusted to 50 mm/s and 20 mm/mV. The atrial Ta wave is not seen, even when the paper scale is changed

lowing equation: corrected PTa=PTa-0.24 (PP-1000), where PP is the average PP interval.

Statistical analysis

Amplitudes and durations are expressed as the mean ± standard deviation. The student t-test was used to analyze paired and unpaired data, and a $p<0.05$ was considered statistically significant. The Shapiro-Wilk test was used for testing the normality of the data and Pearson correlation was used for correlation analyses. The collected data were statistically evaluated using Win STAT in Excel for Windows.

Results

The 12-lead ECG recorded on male subjects in sinus rhythm revealed no trace of cardiac disorders. All ECG data were normally distributed. In order to show the Ta wave, ECGs were recorded in the conventional way and stored in the ECG machine. ECGs were also recorded using the MLL system. Both types of ECG were then replayed at a gain of 20 mm/mV and a speed of 50 mm/s. As expected, the Ta wave was not observable in the standard 12-lead ECG, even on this scale, as shown in Figure 2. The Ta wave in the microvolt range (μV) was clearly seen in the PR segment in all MLL ECG traces except MLL III. Since the left arm electrode and left leg electrode were beside each other in the modified limb electrode position, the MLL III was essentially seen as a flat trace in all recordings.

The Ta wave was non-isoelectric in the MLLs (I, II, aVR, aVL, and aVF), as shown in Figure 3. The comparison of time intervals of atrial and ventricular activation using the standard and MLL ECG recordings for the same healthy subject during sinus rhythm is shown in Figure 4. In the standard ECG, the PR segment is electrically silent, as the presence of Ta wave is not observed as clearly seen in Figure 4, whereas in the MLL ECG, the early part of the Ta wave in sinus rhythm is clearly seen as a depression in the PR segment. The P wave and the Ta wave had opposite polarity in all MLL ECG traces, which is in agreement with previous studies (2-7, 11). In general, the lead aVR, which is actually -1/2 (I + II) in the standard 12-lead ECG, is reflected in the MLL system by having a

Figure 3. Modified limb lead ECG of a 32-year-old male subject in sinus rhythm clearly shows the presence of an atrial Ta wave as a depression in the PR segment of leads I, II and aVL with the corresponding reciprocal elevation in the lead aVR

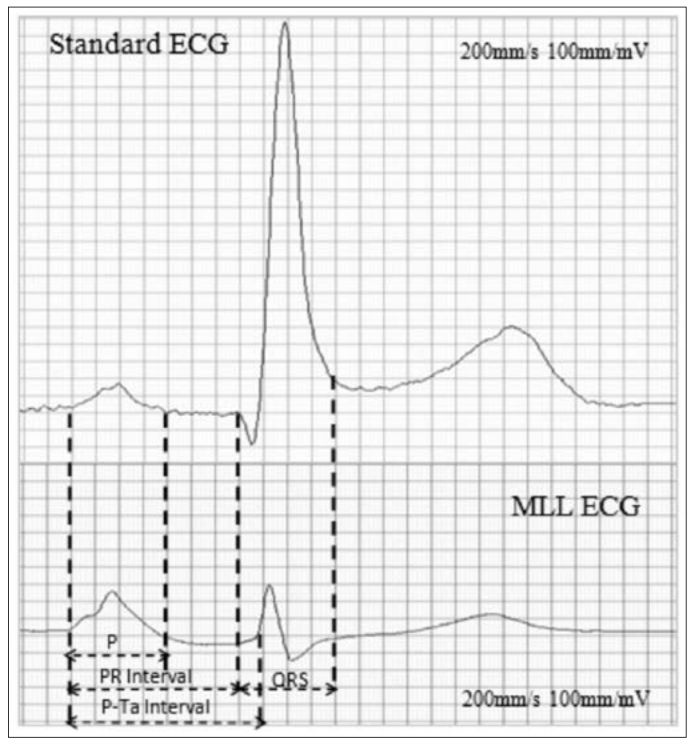

Figure 4. Comparison of time intervals of atrial and ventricular activation using standard (upper) and MLL (lower) ECG recordings. One box has a width of 25 ms and a height of 0.05 mV

negative P wave followed by a positive or elevated Ta wave in the MLL aVR.

The Ta wave is seen in AV block patients, and it has been recorded and analyzed in the standard 12-lead ECG in previous studies (2-7). ECGs from patients with different forms of AV block were recorded with the MLL system in order to assess the duration of the full Ta wave. The PR segment depression in the MLLs (I, II, aVL, and aVF) and the PR segment elevation in the lead aVR is actually the Ta wave, which is clearly noticeable in AV block patients, as shown in Figure 5.

The amplitudes of the P wave and Ta wave of the sinus rhythm subjects and AV block patients of the MLL system are shown in Table 2. The difference between the P wave and Ta wave amplitude in sinus rhythm subjects and AV block patients

Table 2. P wave and Ta wave amplitudes (μV) in sinus rhythm individuals and AV block patients obtained using the MLL system

Measurement	Modified limb lead	Sinus rhythm subjects n=80		AV block patients n=20	
		Mean	SD	Mean	SD
P wave amplitude	I	111	17	143	13.1
	II	118	22	137	9.9
	aVR	-114	18	-132	8.3
	aVL	68	13	80	16.7
	aVF	64	15	69	16.7
Ta wave amplitude	I	-42	6.9	-35	8.6
	II	-43	8.8	-41	9.3
	aVR	37	9.1	38	7.2
	aVL	-44	6.5	-35	9.9
	aVF	-43	7.1	-38	7.9

SD - standard deviation; all values are in microvolts

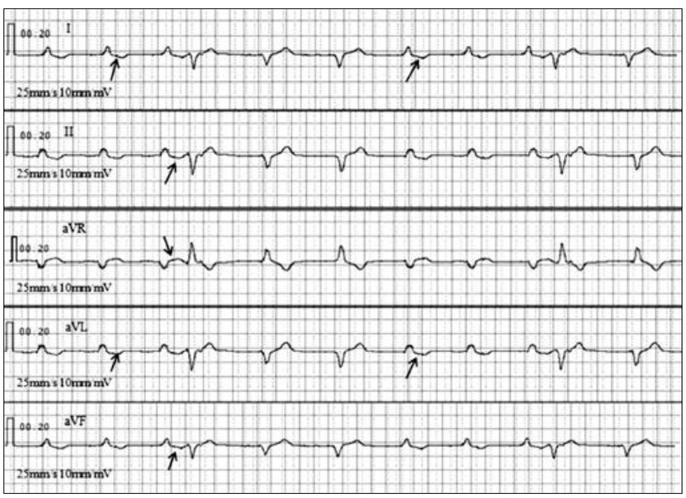

Figure 5. Electrocardiogram of a 67-year-old male AV block patient showing the influence of a negative atrial Ta wave in leads I, II, aVL and aVF and elevated Ta wave in the lead aVR

were found to be statistically significant ($p<0.05$). A correlation was found between the values of P wave amplitude and Ta wave amplitude (Pearson's correlation $r=0.30$, $p<0.05$, $r=0.54$, $p<0.05$) in sinus rhythm subjects and AV block patients, which is in agreement with a previous study done on AV block patients and healthy subjects (7, 11). The P wave, Ta wave duration, P-Ta interval, and the corrected P-Ta interval of the MLL ECG trace of sinus rhythm subjects and AV block patients were found to be statistically significant ($p<0.05$). All values are shown in Table 3.

Discussion

Placement of the modified limb electrodes

The modified limb electrode placement (22) that produces the MLL system is designed according to a) the movement of atrial depolarization and repolarization wavefronts spreading inferiorly from the SA node and b) the direction of the mean electrical vector of atrial depolarization, as well as that of ventricular depolarization. No mean electrical vector for atrial repolarization has been documented so far (24). The propagation of the waves of depolarization and repolarization is parallel to the muscular wall of the atrium, and this phenomenon differs from the ventricles where the depolarization and repolarization waves are perpendicular to the muscular walls of the ventricles (4, 20).

The normal human atrial depolarization wavefront advances from the SA node, resulting in a mean electrical vector that moves in a direction approximately parallel to the mean direction of leads I and II of the MLL. This mean electrical vector produces a positive P wave in modified limb leads I and II. The repolarization Ta wavefront of the atrium initiates from the SA node and follows the same direction as that of the depolarization wavefront (15, 23), producing a negative Ta wave in MLLs I and II, as shown in Figures 3 and 5.

Presence of atrial repolarization in the PR segment

In the present study, the Ta wave observed in the PR segment had a saucer (16)-like depression in leads I and II of the MLL ECG traces. In the lead aVR, the pattern was a mirror image, in which the Ta wave was elevated in the PR segment, which is in agreement with previous studies done on healthy subjects (11-13). The negative Ta wave in the PR segment indicates that the depolarization and repolarization wave pattern from the SA node follows the same sequence in the atria, which is in agreement with a previous imaging study done on one healthy subject (15).

The opposite polarity of the P and Ta wave is in contrast to the case of the QRS complex and T wave (7). Invasive studies of atrial repolarization are rarer, but the results of two studies-one using the monophasic action potential technique and the other using the electrogram-indicate that depolarization and repolarization follow the same sequence in the atria (25, 26). The invasive data that exist are in agreement with the findings in the present study and in previous studies (2-10). Holmqvist et al. (7) proposed that some form of separation of the atrial and ventricular ECG components is needed to enable ECG analysis of

Table 3. P wave, Ta wave, P-Ta interval, and the corrected P-Ta interval durations (ms) in sinus rhythm subjects and AV block patients obtained using the MLL system

Measurement	Modified limb lead	Sinus rhythm subjects n=80		AV block patients n=20	
		Mean	S.D.	Mean	S.D.
P wave duration	I	87	5.91	102	4.48
	II	88	6.15	105	4.19
	aVR	88	3.49	105	4.92
	aVL	88	5.03	102	4.30
	aVF	88	6.68	104	4.68
Ta wave duration	I	108	4.77	312	26.7
	II	108	4.84	314	27.1
	aVR	109	4.29	323	28.2
	aVL	109	4.73	311	31.4
	aVF	109	4.67	312	25.2
P-Ta duration	I	195	5.76	414	27.6
	II	196	5.61	419	28.3
	aVR	197	4.78	428	29.5
	aVL	197	4.80	413	31.5
	aVF	197	4.78	416	26.8
Corrected P-Ta duration	I	223	8.32	462	30.2
	II	233	6.57	456	31.5
	aVR	247	7.89	478	29.8
	aVL	228	7.23	444	34.6
	aVF	257	6.31	470	29.6

SD - standard deviation; all values are in milliseconds

the Ta wave during normal AV conduction. This is achieved in sinus rhythm subjects. In sinus rhythm, the observed Ta wave in the PR segment represents the early part of atrial repolarization. Generally, part of the Ta wave is superimposed onto the QRS complex and the ST-segment (4). In the present study, even though the QRS amplitude is reduced, the later part of atrial repolarization in the QT interval is unnoticeable.

Impact of the atrial Ta wave in the PR Interval

The Ta wave can be observed in the PR interval of subjects during sinus rhythm, as shown in Figure 3. The Ta wave peak amplitude was clearly seen. The P wave onset to the observable Ta wave end is said to be the "P-Ta interval," and the P wave end to the observable Ta wave end is noted as the "Ta duration" in this study. There are considerable difficulties in measuring the PR interval, P-Ta duration, and Ta duration in the MLL ECG. Such details have not been reported previously. In this study, the findings of the Ta wave duration in AV block patients show that there is an increase in atrial repolarization duration, because the entirety of the Ta wave can be observed. This is generally due to the fact that the Ta wave in AV block patients is not obscured by the QRS complex, whereas the Ta wave recorded in healthy subjects shows only the observable Ta wave duration, as the QRS complex obscures the later part of the Ta wave. In AV block patients, the full Ta wave was clearly visible, and the duration was approximately 3 times longer than the P and Ta wave duration of subjects in sinus rhythm.

Study limitations

No female subjects were involved in this study. The later part of the atrial Ta wave is not observed in sinus rhythm subjects. The results of the present study are valid only for resting, supine male subjects in sinus rhythm and in patients with AV block.

Conclusion

In this study, the observations during the PR segment in the MLL ECG trace confirm that the Ta wave is present during sinus rhythm. The observable Ta wave in the PR segment was of opposite polarity to the P wave in all MLL ECGs that were analyzed. This is in agreement with previous studies done on the Ta wave. A group (n=20) of AV block patients was studied to assess the Ta wave in those patients. In the present study, the MLL system was used to record the Ta wave in sinus rhythm subjects. The lead system needs to be evaluated in patients, perhaps with atrial infarction or even pericarditis, to see what changes might be found in the P-Ta segment.

Clinical implications

Since atrial repolarization waves are often hidden within the QRS complex, they remain difficult to analyze. Better delineation of atrial Ta waves may help to decode the mysteries surrounding atrial repolarization. Repolarization abnormalities are the major electrophysiological substrate for arrhythmias. Analyzing the Ta waves helps in understanding the mechanism of the onset of atrial arrhythmias.

The Ta wave measurement will be especially important in decoding the mechanism for the triggers of atrial fibrillation, which is a very common clinical problem. Precise measurement of Ta waves will also help to measure the P-Ta interval, which is the atrial equivalent of the QT interval. Analyzing the P-Ta interval dynamics will shed further insight into the mechanism of atrial tachycardia. Further studies are warranted to determine the effect of various anti-arrhythmic drugs on the Ta wave duration.

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