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Optimum Lead Positioning for Recording Bipolar Atrial Electrocardiograms during Sinus Rhythm and Atrial Fibrillation

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Summary

Background: To date, Holter monitoring has been predominantly utilized in the investigation and monitoring of ventricular arrhythmias and myocardial ischemia. Whether currently employed lead configurations are optimal for recording atrial electrocardiograms (ECGs) is unknown.

Hypothesis: This study was undertaken to determine which conventional and novel lead configurations are optimal for recording atrial electrical activity during sinus rhythm and atrial fibrillation.

Methods: Recordings were performed on eight healthy volunteers in sinus rhythm and four patients in atrial fibrillation. Each subject had 10 ECGs of three bipolar and three augmented unipolar leads recorded during supine rest, while rising to upright, and during standing rest, yielding a total of 60 leads (30 bipolar leads). Each tracing was inspected by two observers, and parameters such as P-wave amplitude and duration, whether the P-wave onset was clearly seen, atrial fibrillatory-wave amplitude, and amplitude of noise during standing were scored.

Results: Leads recording inferiorly and leftward orientated bipoles provided the best registration of sinus P waves. The P-wave amplitude in the standard bipolar C5 lead (0.12 ± 0.02 mV) was, however, inferior to others such as recordings between C1 and C6 positions (P-wave amplitude 0.16 ± 0.02 mV) or from below the right clavicle to the left upper quadrant of the abdomen (0.16 ± 0.01 mV). Optimal recording of fibrillatory waves was from different leads, such as a bipole from below the left clavicle to a low C1 position (fibrillatory wave amplitude 0.27 ± 0.03 mV).

Conclusion: When Holter recordings are performed for the investigation of atrial arrhythmias, nonstandard lead configurations provide superior recording of atrial electrical activity. We advocate the use of electrodes positioned from C1 to C6, from below the left clavicle to a low C1 position, and a vertically orientated lead from the manubium to the twelfth vertebra or the xiphisternum.

Key words: ambulatory electrocardiography, atrial arrhythmias, atrial fibrillation

Introduction

Holter recordings are a useful tool for the noninvasive investigation of cardiac rhythm disturbances. To date, research has centered on ventricular rhythm disturbances[1–3] and the detection of asymptomatic myocardial ischemia.[4–8] It is therefore not surprising that currently employed lead configurations are designed to optimize the identification of ventricular depolarization and ST-segment depression, respectively. Research into the field of atrial arrhythmias, and in particular atrial fibrillation (AF), has expanded in recent years, and therefore the definition of the optimal lead position for recording of atrial signals becomes relevant.

Several features of the sinus P wave and other atrial events are of interest during recordings. For the automated detection and possible signal averaging of P waves, features such as magnitude of deflection and area of the P wave are important. The presence of a well-defined P-wave onset will further facilitate this process, whether template matching or deflection threshold methods are utilized for P-wave timing. Nonsinus atrial activity, including ectopic beats and atrial fibrillation, pose other requirements. For the differentiation of sinus from nonsinus beats, maximizing the three-dimensional vector angle between recorded electrocardiograms (ECGs) is of value. In a three-lead recording, utilizing an or-

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thogonal lead configuration would be the ideal, but several practical restrictions come into play. True orthogonal lead systems, such as the Frank XYZ system,[9] are not based upon simple bipolar leads but instead incorporate multiple electrodes connected by resistors to generate each lead. These are not incorporated into current Holter systems. More important is the impractical nature of prolonged recordings with electrodes on the back of the thorax and on the neck.

The detection of large amplitude fibrillatory waves is important if these are to be analyzed. Recently, noninvasive assessment of atrial electrophysiology during AF has been reported by Holm *et al.*,[10] and applications for this and similar techniques may evolve. It cannot be inferred that the ideal leads for recording of sinus P waves are identical to those in which fibrillatory activity is seen most clearly.

Atrial depolarization results in a deflection on the surface ECG of approximately 0.1 mV. This is of the same order as that of electrostatic noise seen routinely in recordings arising from imperfect skin preparation, deterioration of skin contact during a prolonged recording, and skeletal muscle myopotentials. The propensity to this noise is, however, not identical at all sites, as deterioration in contact during recording may be expected to occur, particularly when electrodes are positioned over sites where skin is mobile and prone to lateral shear forces. The curvature of the contact surface and the prominence of the site in terms of catching on clothing will also have an effect. The proximity of large skeletal muscle groups will obviously affect the amount of muscle myopotential activity.

This study investigated the value of multiple bipolar lead configuration for the detection of sinus P waves and atrial fibrillation. To allow limited inferences regarding the practicalities of utilizing lead positions during Holter recordings, the magnitude of baseline noise was measured during supine rest, during the adoption of upright posture, and during upright rest.

Methods

Recordings were performed on healthy volunteers in sinus rhythm and on patients in AF. Skin preparation involved shaving, if necessary; cleaning with isopropyl alcohol wipes; and gentle abrasion prior to application of standard electrodes (Blue Sensor, Medicotest, A/S, Ølstykke, Denmark). Electrocardiograms were recorded on paper using a Mingograph 7 (Siemens Elema AB, Solna, Sweden) as a continuous six-lead recording of the three bipolar leads and the three augmented unipolar limb leads. Electrocardiograms were printed using the Cabrere configuration (aVL, I, aVR, II, aVF, III) to facilitate detection of trends within a particular three-lead configuration. The bipolar leads were used for primary analysis, with the augmented unipolar limb leads included to suggest possible additional lead configurations of interest. Each recording was begun with the subject resting supine; without discontinuing recording, subjects were then asked to rise to a standing position and several seconds of recording were performed with the subject standing quietly at rest.

The electrode positions utilized are shown in Figure 1. In all cases, the earth electrode was positioned on the lateral upper right quadrant or the abdomen. Lead combinations were chosen as modifications of current configurations or to investigate bipoles of hypothetical value, as outlined later. The 10 combinations of three bipolar ECGs are given in Table I.

Recordings performed during sinus rhythm (SR) were initially assessed to ascertain those in which a P wave was identifiable. In those recordings, the P-wave height and duration were measured manually with the optional aid of a magnifying ruler. Whether or not there was clear P-wave onset was also recorded; P-wave onset was defined as initial deflection of the P wave from the baseline $\geq 45°$. The amount of noise was measured in the supine position, during adoption of upright posture, and while upright. This was assessed by measurement at a typical baseline region determined by observer

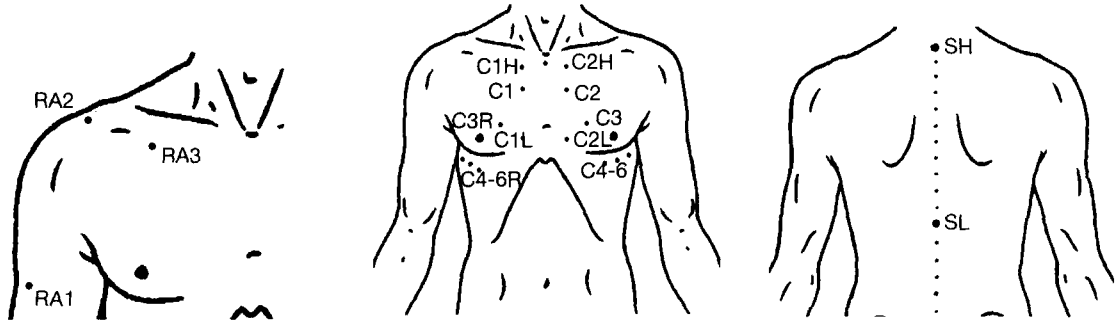

FIG. 1 Lead positions utilized in this study: Limb leads (right-sided leads illustrated only) were on the lateral aspect of arm, below insertion of deltoid (LA1 and RA1), on the upper aspect of scapula, just posterior to the distal end of the clavicle (LA2 and RA2), and below the clavicle, at two-thirds of the distance to its lateral end (LA3 and RA3). Leads marked C1 to C6 represent the standard lead positions for chest leads, with the suffix "R" (e.g., C6R) denoting the mirror image right-sided lead. The suffixes "H" and "L" are used to denote high and low positioning, respectively, of the C1 and C2 leads. Instead of using the fourth intercostal space, the leads were placed 2 cm below the clavicle for high leads and in the sixth intercostal space for low ones. "M" denotes a lead positioned over the manubrium sterni. "SH" and "SL" are leads positioned just lateral to the vertebral column. "SH" is adjacent to the seventh cervical vertebra, and "SL" next to the twelfth thoracic vertebra. LL (not shown) was positioned inferiorly and laterally on the costal margin.

TABLE 1 Ten combinations of three bipolar electrocardiograms

ECG No.	RA electrode	LA electrode	LL electrode
1	LA3	RA3	LL
2	LA2	RA3	C1L
3	LA2	C5R	C5
4	C2H	RA2	C5
5	RA1	RA2	LL
6	C6R	RA2	C6
7	C1	SH	C6
8	C1H	SH	C2H
9	C1L	SH	SL
10	M	SH	SL

Positions of the electrodes used in this study. Each lead configuration provided three unipolar and three bipolar electrocardiograms (ECGs). The bipolar electrocardiogram from RA1 to RA2 in ECG 5 was obviously of very low amplitude and was thus excluded from analysis. Similarly, both ECG 9 and 10 contain a recording from SH to SL, and the latter was therefore excluded from analysis.
Abbreviations: RA = right arm, LA = left arm, LL = left leg.

visual selection. Finally, whether the R wave was of > 1 mV amplitude was recorded. All recordings were analyzed independently by two observers (JW and MG).

Each recording performed during AF determined whether fibrillation waves could be identified. If this was possible, then the maximum and minimum amplitude of the waves was scored by assessing deviation from baseline over windows of 200 ms. Whether the R wave was > 1 mV was recorded, but no attempt was made to score noise, as this measurement would have been confounded by fibrillatory waves.

Data were analyzed for each lead to determine the proportion of recordings in which the P wave was identifiable, the mean height of P waves, the mean duration of P waves, and the proportion of recordings in which the onset was clear. A composite "P-wave index" was derived, which represents the product of amplitude, duration, and a derivative of the proportion of those with a clear onset:

$$\text{P-Wave Index} = \frac{\sum_{1}^{1} P\,Amp}{N} \times \frac{\sum_{1}^{N} P\,Durn}{N} \times \left(1 + \frac{\sum_{1}^{N} P\,Onset = clear}{N}\right),$$

where N = 16, the total number of values per lead (8 patients, 2 observers). The use of one plus the fraction in which P-wave onset was clear, rather than just the fraction itself, was employed to reduce the effect of this parameter on the final "P-wave index." It was felt that since the determination of this parameter was more subjective and of less proven value, it should thus receive less weight than P-wave amplitude and duration.

The recordings in atrial fibrillation were analyzed to determine the proportion of recordings in which fibrillatory waves could be seen, the mean maximal fibrillatory amplitude, and the mean of the average of the maximum and minimum amplitude. During both SR and AF recordings, the proportion of recordings in which the R wave was > 1 mV in amplitude was assessed. Mean and standard deviation of noise while supine, during rising, and during standing rest were determined for all leads.

Statistical Methods

Mean values were calculated for each of the measured parameters. For all independent continuous data (P-wave amplitude, P-wave duration, noise, and fibrillatory-wave amplitude), a standard error (SE) was calculated. This represents the SE of the difference between the measurement and the mean of all measurements in that individual. The average of the SEs from the two observers was calculated and is quoted throughout.

Results

Suitable recordings were obtained in eight healthy volunteers (2 men, mean age 37 years, range 27–50) and four patients in AF (1 man, mean age 68 years, range 52–86).

The measurements from the 11 bipolar leads and the 3 augmented unipolar leads with the largest mean P-wave amplitude are presented in Table II and Figure 2. The vector of the bipole in the three best leads and many of the rest was orientated inferiorly and leftward. The remaining leads demonstrating large P-wave amplitudes generally had an inferior, or inferior and rightward axis. Bipoles utilizing an electrode positioned on the back were capable of recording useful signals. The electromyographic interference during posture change is greatest when both electrodes are positioned in peripheral locations, and least when both are on the bony thorax (Fig. 2C). No strong relation was found between P-wave parameters and maximal atrial fibrillatory wave amplitude. Although there was a trend for leads with a larger AF-wave amplitude also to have a higher P-wave amplitude and P-wave index, this correlation was nonsignificant (Fig. 3). Most of the leads demonstrating the largest mean fibrillatory-wave amplitude had mediocre scores on P-wave amplitude and P-wave index. For example, the bipolar lead with the highest mean fibrillatory amplitude, LA2 to C1L, had a mean P-wave amplitude of 0.97 mV (jointly ranked 12th of 28 bipolar leads) and an index of 3.6 (ranked 10th).

The values of noise during lying at rest, noise during standing at rest, and of minimal fibrillatory-wave amplitude seen did not add to the data presented, and are therefore not shown.

Minor adjustments in the positioning of the limb lead electrodes did not result in consistent differences in the quality of atrial recordings. Recording from different right atrial positions to the LL electrode gave a mean P-wave amplitude of 0.16 mV when the electrode was positioned below the clavicle (SE 0.01, P index 7.3, fibrillation amplitude 0.16 ± 0.01), 0.12 mV when on the lateral end of the clavicle (SE 0.02, P index 3.8, fibrillation amplitude 0.11 ± 0.02), and 0.12 mV when on

TABLE II Values for parameters relating to the P wave, fibrillation waves, R wave, and noise during rising for the 10 bipolar leads and the 3 augmented unipolar leads with the highest mean P-wave amplitude

	P wave					Fibrillation		R wave	Noise on
	Seen (%)	Onset OK (%)	Amplitude (mV)	Duration (ms)	Index	Seen (%)	Maximum amplitude (mV)	OK (%)	rising (mV)
C1 to C6	100	93.8	0.163	87.5	6.89	100	0.219	100	0.40
RA3 to LL	100	93.8	0.159	95.0	7.33	100	0.156	100	0.86
SH to C6	100	81.8	0.141	93.8	5.97	87.5	0.125	100	0.40
M to SL	100	87.8	0.141	86.3	5.69	100	0.181	56.3	0.34
RA1 to LL	93.8	62.5	0.122	88.0	4.08	87.5	0.119	62.5	0.93
RA2 to C5	87.5	68.8	0.119	98.6	4.32	100	0.125	81.3	0.56
RA2 to LL	93.8	62.5	0.116	86.7	3.82	100	0.231	68.8	0.86
RA2 to C6	93.8	62.5	0.113	88.0	3.77	100	0.113	75.0	0.38
LA3 to LL	100	75.0	0.106	83.8	3.89	100	0.163	68.8	0.90
C1L to SL	93.8	62.5	0.106	74.7	3.02	100	0.225	62.5	0.38
LA2 to C5	100	56.3	0.103	85.0	3.42	100	0.113	81.3	0.61
C1/SH to C6	100	75.0	0.138	88.8	5.34	100	0.138	87.5	0.37
LA3/LL to RA3	100	75.0	0.128	96.3	5.40	100	0.119	75.0	0.61
SH/C6 to C1	100	93.8	0.116	81.3	4.55	87.5	0.106	93.8	0.33

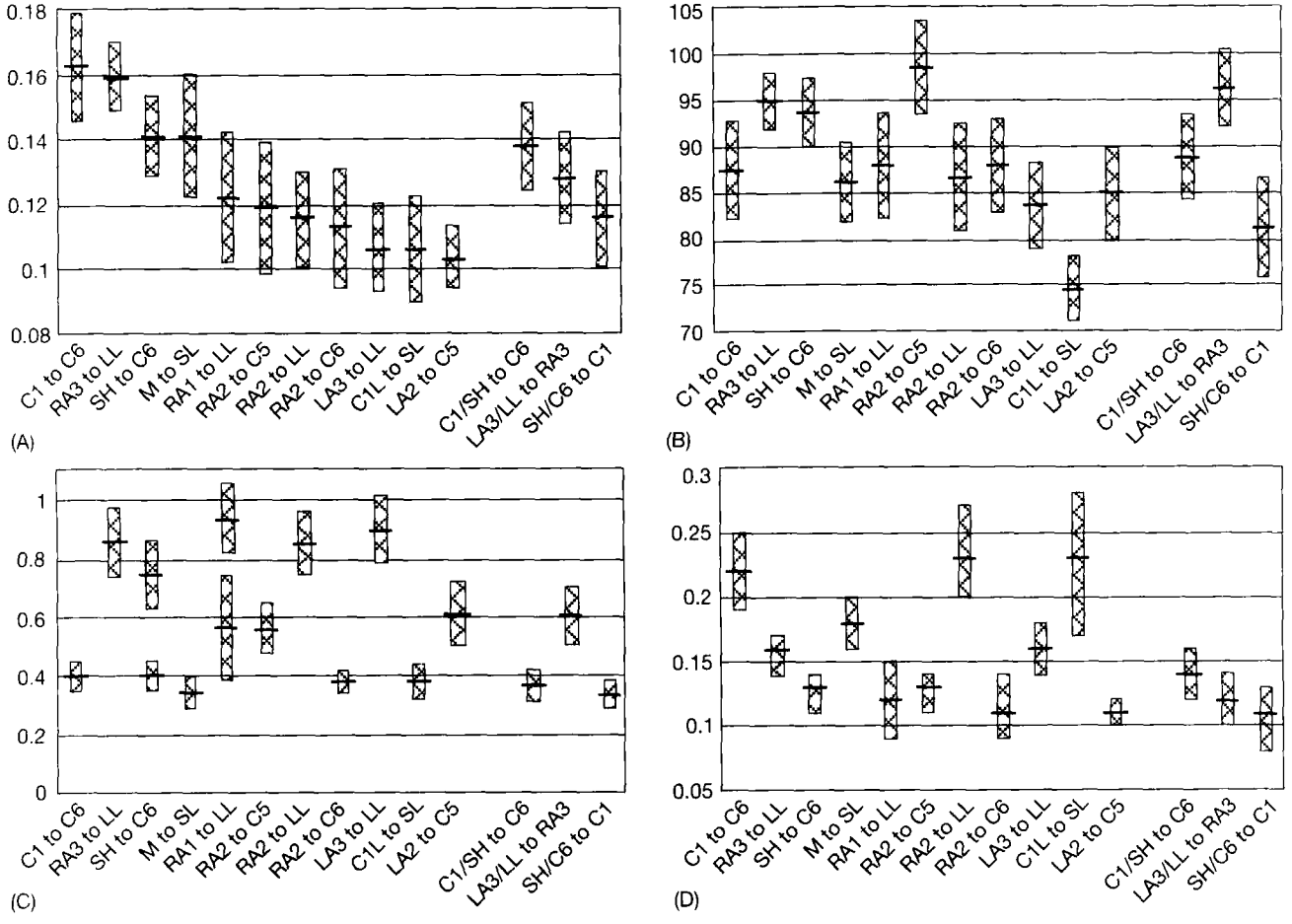

FIG. 2 The figure shows the mean values for leads with the highest mean P-wave amplitude. In each case the mean is shown by a horizontal bar, with the vertical bar representing the standard error of the mean. (A) Mean P-wave amplitude (mV), (B) P-wave duration (ms), (C) electrocardiographic noise seen during rising (mV), and (D) the maximal fibrillatory-wave amplitude. The P-wave index is a derived measure, giving a combined, weighted parameter sensitive to P-wave amplitude, P-wave duration, the proportion of ECGs in which the P wave was identifiable, and the proportion in which the P-wave onset was clearly defined.

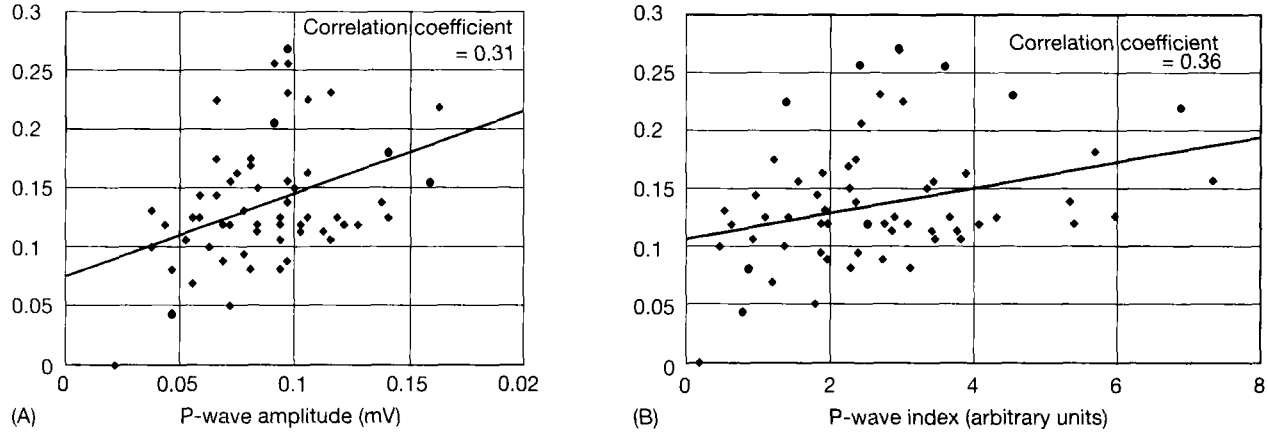

FIG. 3 The values of (A) P-wave amplitude and (B) P-wave index plotted against maximal fibrillatory-wave amplitude (mV) in both cases for 58 of the leads (28 bipolar and 30 augmented unipolar, one bipolar lead excluded as it represented recording from almost adjacent sites). As can clearly be seen, there is poor correlation between the two values, confirmed by the calculated correlation coefficients. Note that the leads that register the largest fibrillatory-wave amplitude record only moderate amplitude P waves.

the upper arm (SE 0.02, P index 4.1, fibrillation amplitude 0.12 ± 0.03). However, when recording to an electrode at the right arm position, the lateral end of the left clavicle position (P-wave amplitude 0.08 ± 0.01, P index 2.4, fibrillation amplitude 0.09 ± 0.03) was superior to positioning the electrode below the middle of the left clavicle (P-wave amplitude 0.07 ± 0.01, P index 2.0, fibrillation amplitude 0.09 ± 0.02).

An example of the difference between a standard CM5 lead and the C1 to C6 during sinus rhythm, and left clavicle to low C1 position is illustrated in Figure 4.

Discussion

The optimum position for bipolar leads is dependent on the purpose of the recording and the setting in which data are to be acquired. If myocardial ischemia is the primary purpose for the study, the CM5 lead in particular has been found to be reliable and useful.[11,12] This study suggests that conventional Holter positions are not optimal for P-wave and atrial fibrillatory-wave recording. A minor modification, using either a modified lead C6 (positive pole at C6 and negative at C1) or a modified lead II (positive pole below the left ribs on the lateral upper abdominal quadrant, negative pole below the right clavicle) resulted in improved recording of P-wave activity and, in this study, improved rates of recording large QRS complexes. The modified C6 has the advantage of low levels of myopotential noise.

The other important finding was that the optimum lead position for detecting fibrillatory-wave activity differs from the lead in which the largest P waves are seen. Although nonsinus activity other than AF was not examined in this study, it is clear that features such as atrial flutter and junctional ectopics are likewise unlikely to be optimally recorded in leads optimized for sinus beats. Thus, we would recommend that the preferred second lead position should be a low C1 position, with the positive pole positioned at the sixth rib space to the right of the sternum and a negative pole below the left clavicle. This will provide an approximately orthogonal recording to a modified C6 lead and was shown to provide excellent recording of fibrillatory activity. For assessing the origin of atrial tachycardia, the unipolar V_1 lead is of great value,[13] and this was found by Holm *et al.*[10] to be the lead correlating best with right AF cycle length. It is therefore not surprising that a bipolar modification of V_1 should be recommended for recording nonsinus atrial activity.

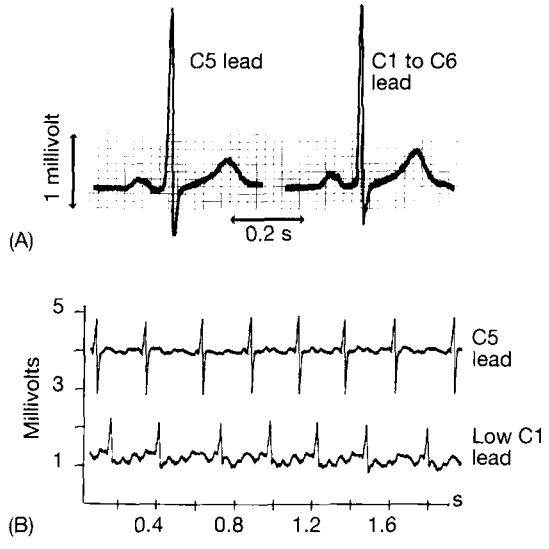

FIG. 4 Examples of the difference between the suggested "C1 to C6" and the "left mid-clavicular to low C1" bipolar leads in P-wave and fibrillation-wave registration, respectively, compared with a conventional C5 lead. (A) Two magnified QRS complexes from the same patient; (B) two longer duration smaller scale strips from a patient with atrial fibrillation.

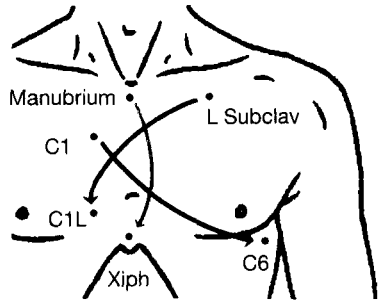

FIG. 5 The lead configuration recommended as a result of this study for ambulatory recordings performed to investigate atrial arrhythmias is shown. The two primary leads are shown in black, with the arrowhead indicating the position of the positive pole. Where a third channel is available, the negative pole should be positioned at the manubrium, and the positive pole over the twelfth vertebra for short-term recordings or the xiphisternum for longer-term recordings (shown in gray).

If a third lead is required for short- or medium-term recordings in which it is feasible to record with an electrode positioned on the back, then this option should be considered. Such leads allow excellent recording of both sinus and fibrillatory activity. We would recommend that the negative pole be positioned over the manubrium sterni and the positive lead just lateral to the twelfth vertebra. For prolonged ambulatory monitoring, a vertically oriented lead (manubrium to xiphisternum) has been shown by others to provide excellent recording of sinus activity,[14] although that study did not investigate any nonsinus activity.

Thus, this study has shown that excellent registration of atrial electrical activity can be achieved with the combination of a modified C6, the low C1 lead, and a vertically orientated lead. This will provide a semiorthogonal lead configuration, maximizing independent data collection (Fig. 5).

Limitations

The fact that unipolar and bipolar recordings were analyzed jointly may have induced slight underestimation of correlations and standard errors since data are not truly independent. The choice to quote standard error in relation to difference of measured values from mean values in individual patients, rather than to all measurements of a lead, represents a compromise. It was felt that the interpatient variability of surface ECG signals would create a false impression of the measurement error. The chosen comparison interrogates the error of the ranking of the lead among all investigated leads and is thus a truer reflection of the relevant criteria. No validation exists for inferring wider significance of ECG noise during rising. The ability to discriminate clearly whether both, one, or none of the leads were positioned on the thorax suggests, however, that such a technique may be of value. Finally, the population size for the AF aspect was relatively small. While this limits the absolute power of the study to determine the optimal sites for registering fibrillatory activity, this was not the primary intent of the study and, we feel, does not invalidate the conclusions and recommendations made.

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