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Comparison of Laplacian and Bipolar ECGs for R-wave Detection during Noise

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Abstract—**Body surface Laplacian mapping localizes cardiac activity and provides more detailed distributions compared to body surface potential mapping. Systematic comparison of the performance of bipolar and Laplacian ECGs during noise has not been performed. To determine whether Laplacian ECGs (2.5cm diameter concentric rings) can reduce noise (myopotential and motion artifacts) and improve signal to noise ratio (SNR) compared to bipolar (4cm spacing) ECGs, Laplacian and bipolar ECGs were recorded from the anterior (precordial V_3) and lateral (precordial V_6) chest regions in 25 patients undergoing posture changes and in-office exercises. Mean peak-to-peak (V_{pp}), root mean square noise ($Noise_{rms}$) and SNR were computed across all activities and patients. Sensing performance using an R-wave detector with an auto-adjusting exponentially decaying threshold was assessed. Across all maneuvers, mean V_{pp} was larger for the bipolar ECG compared to the Laplacian ECG on the anterior (0.65±0.07 vs. 0.14±0.07 mV, p<0.05) and lateral (0.65±0.07 vs. 0.05±0.07 mV, p<0.05) regions. Laplacian ECGs resulted in least $Noise_{rms}$ compared to bipolar ECGs (anterior: 0.02±0.01 vs. 0.05±0.01, p<0.05; lateral: 0.01±0.01 vs. 0.07±0.01, p<0.05). Bipolar and Laplacian SNRs were comparable on the anterior chest (14.05±0.95 vs. 13.49±0.95, p=NS). On the lateral chest, bipolar SNR was larger than Laplacian SNR (13.78±0.95 vs. 8.67±0.96, p<0.05). Laplacian SNR on the anterior chest was larger compared to the lateral chest, confirming that Laplacian ECGs are sensitive to mapping location. Sensing performance showed that bipolar ECGs resulted in marginally superior sensing accuracy compared to Laplacian ECGs. In conclusion, Laplacian ECGs offer no advantage in SNR compared with standard bipolar ECGs.**

I. Introduction

Cardiac arrhythmias remain a leading cause of sudden death and disability[1] (>300,000/yr in the US alone). The Electrocardiogram (ECG) is a noninvasive body surface measurement aimed at characterizing cardiac electrical activity[2-3]. It depicts the temporal variation of the potential at a specific site on the body surface. Clinically, cardiac electrical activity is measured using the 12 lead ECG. Body surface potential mapping (BSPM) involves recording ECGs from multiple sites on the body surface. BSPM offers greater resolution and specificity compared to the conventional 12 lead ECG[4].

Body surface Laplacian mapping localizes cardiac activity from the body surface and provides more detailed potential distributions compared to body surface potential mapping[5]. In addition, the Laplacian ECG is known to provide adequate signal to noise ratio and reduce myopotential noise[5].

We tested the hypothesis that Laplacian ECGs can reduce noise (myopotential and motion artifacts) and improve signal to noise ratio (SNR) compared to bipolar ECGs in patients undergoing posture changes and in-office exercises.

II. Methods

A. Patient Population

Twenty-five patients (3 female and 22 male, age 67±14 yrs, and left ventricular ejection fraction 35±9 %) were enrolled in this study during an in-office follow up procedure following a device implant. All patients had an implantable cardioverter defibrillator (ICD) Marquis or InSync CRT device, Medtronic, Inc. Informed consent was obtained from all patients according to the Memorial Healthcare System Investigational Review Board. No adverse events were reported.

B. Clinical Protocol

Patients underwent posture changes and in-office exercises during follow-up to study the effect of motion artifacts and myopotential noise on Laplacian and bipolar ECGs. Posture changes included patients lying on right side, left side, supine, sitting, and standing. Patients were also asked to perform isometric exercises (push-pull and Valsalva) and lift weights (2-3 lbs). By performing controlled posture and in-office exercises, we were able to relate observed changes in ECG features to specific maneuvers. Fig. 1 describes the electrode setup.

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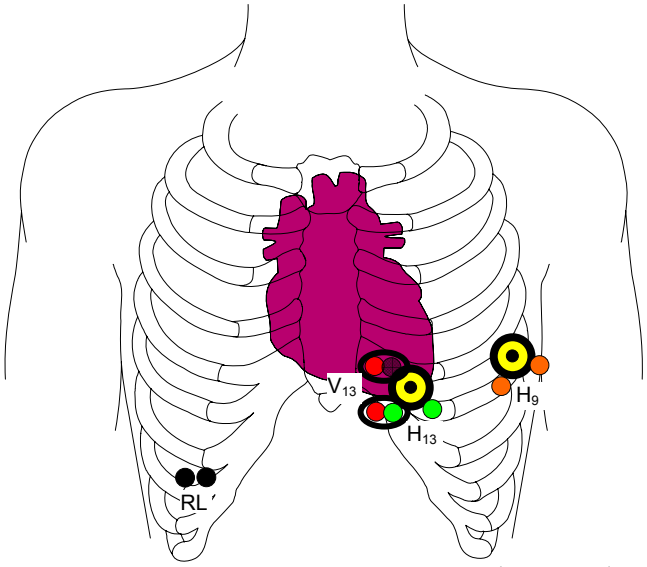

Fig. 1 ECGs layout. Laplacian electrodes (yellow) at 3rd (L_{13}) and 6th (L_9) precordial lead positions. Bipolar ECGs adjacent to L_{13} (V_{13}, vertical; H_{13}, horizontal). Bipolar ECG adjacent to L_9 (H_9, horizontal). RL, right leg.

C. Data Acquisition

Body surface ECGs from two 2.5cm diameter active Laplacian (Bioengineering SenseTech Inc., Taipei, Taiwan [non-FDA approved]) electrodes (L_{13}, located at the 3rd precordial lead position; L_9, at the 6th precordial lead position), three bipolar (4cm spacing) electrodes (V_{13}, vertically oriented adjacent to L_{13}; H_{13}, horizontally oriented adjacent to L_{13}; H_9, horizontally oriented adjacent to L_9) were acquired (Fig. 1). The Laplacian and ECG electrodes were placed in the designated locations (Fig. 1) guided by the Medtronic Uni-Lead Precordial ECG Electrode System. The patient's skin was prepped with alcohol and when needed shaved and lightly abraded. The electrodes were held in place using a Kendall cotton roll with an Ace bandage wrapped around the patient's chest. Care was taken to maintain comfort and not constrain patient's respiration. The ECGs and device telemetry were recorded with two DR190 holters (Northeast Monitoring, Maynard, MN) synchronized using event markers. A battery powered adaptor unit was built to provide power to the actively amplified Laplacian electrodes and attenuate the amplified signals to levels acceptable to the Holter recorder.

D. Data Analysis

All ECGs were acquired simultaneously and bandpass filtered (2-100Hz Kaiser FIR). A 60Hz Notch filter was applied to eliminate EMI. ECGs were inspected for quality and segments with artifacts (exhibiting saturation or loss of signal) were discarded. For each event (posture change, isometric exercise, weight lifts, etc.) we chose an analysis window that centered on the activity at hand. The analysis window duration ranged from 5 to 25 sec depending on the maneuver. Pacing spikes were identified and manually removed. Premature ventricular complexes and paced ventricular beats were included in the analysis. Peak-to-peak R-wave (V_{pp}) was automatically determined within the analysis window. The detected R-waves were then inspected for accuracy. Root mean square noise ($Noise_{rms}$) was computed between each two consecutive R-waves. Although other techniques for estimating noise levels exist, the $Noise_{rms}$ metric is widely utilized in standard body surface Laplacian mapping studies which form the basis for comparison to our study. Signal to noise ratio (SNR) was computed as $V_{pp}/Noise_{rms}$ for each RR interval and averaged over the entire analysis window. Statistical analysis was performed using analysis of variance method where the patient effect was considered as a random effect. Sensing performance was assessed using an R-wave detector with an auto-adjusting exponentially decaying threshold. A sensed event was determined based on the crossings of the filtered (10-32Hz) and rectified ECG with the threshold. Within the analysis window, sensed events were qualitatively evaluated for accuracy by visual inspection. If a sensed event fell within ±50ms of an R-wave, then the event was classified as a true positive (TP), otherwise, it was a false positive (FP). If an actual R-wave was not sensed, then the event was classified as a false negative (FN). Sensitivity (Sens) and positive predictivity (PPV) were then computed for each ECG during each event according to:

$$Sens = \frac{TP}{TP + FN} \text{ and } PPV = \frac{TP}{TP + FP}$$

III. Results

Of the 25 patients enrolled in the study, fifteen provided complete data sets for analysis. Data acquisition errors and signal dropouts resulted in incomplete data for the remaining 10 patients.

A. Peak-to-peak R-wave Amplitude (V_{pp})

Mean V_{pp} for Laplacian ECGs during posture changes (sitting, standing, supine, lying on right, and left side) was 0.14mV and 0.05mV for L_{13} and L_9 respectively. As patients shifted from supine to left side, bipolar ECGs showed an increase in mean V_{pp}, whereas mean V_{pp} for Laplacian ECGs remained stable. Across all maneuvers, mean V_{pp} was larger for V_{13} (0.65±0.07 mV) and H_{13} (0.40±0.07 mV) compared to L_{13} (0.14±0.07 mV, $p<0.05$). On the lateral chest, mean V_{pp} for H_9 was larger compared to L_9 (0.65±0.07 vs. 0.05±0.07, $p<0.05$).

B. Noise ($Noise_{rms}$)

Fig. 2 shows that the Laplacian ECGs resulted in least $Noise_{rms}$ on average compared to the corresponding bipolar ECGs across all patients and maneuvers. $Noise_{rms}$ did increase for all ECGs during isometric exercises such as push, pull, and Valsalva (Fig. 3).

C. Signal to noise ratio (SNR)

Fig. 4 shows that SNR is comparable on the anterior chest

between L_{13}, V_{13} and H_{13} (13.49±0.96, 14.05±0.95, and 12.83±0.95 respectively). No significant benefit in SNR was obtained with L_{13}. On the lateral chest, L_9 resulted in least SNR (8.68±0.96) compared to H_9 (13.78±0.95, $p<0.05$). SNR for L_{13} was significantly larger than L_9 ($p<0.05$).

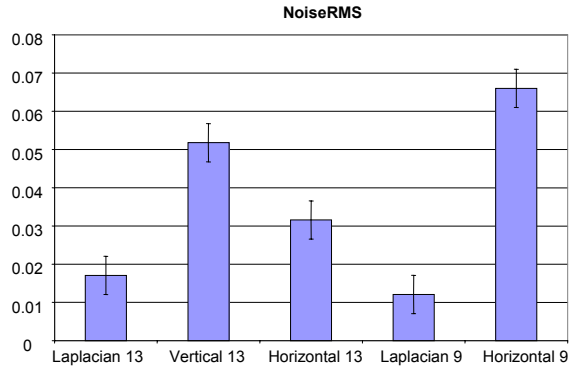

Fig. 2 $Noise_{rms}$ over all patients and all maneuvers.

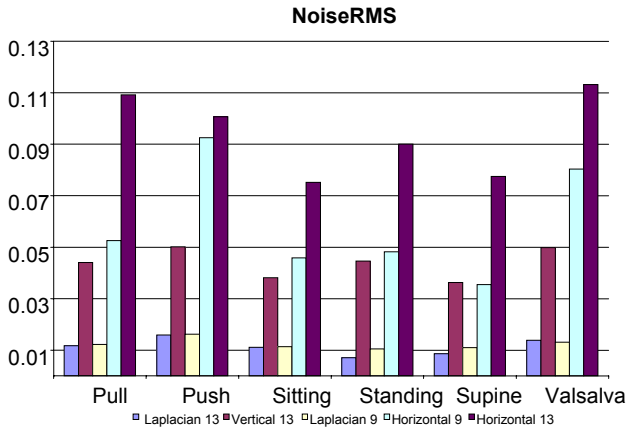

Fig. 3 $Noise_{rms}$ over all patients during isometrics and posture. Note increase in $Noise_{rms}$ during isometrics (push, pull and valsalva) compared to sitting, standing and supine.

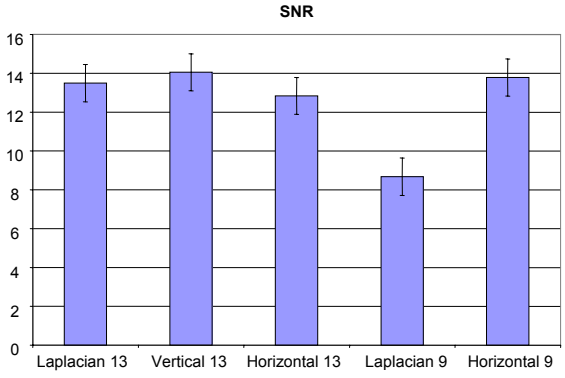

Fig. 4 SNR over all patients and all maneuvers

D. Sensing performance

Figs. 5 and 6 summarize the mean sensitivity and PPV over all patients and maneuvers/events. Overall, sensitivity was best for V_{13}, followed by H_{13}. Despite having an adequate SNR, L_{13} did not provide optimal sensing due to its susceptibility to noise. The estimated mean sensitivity of L_{13} was marginally lower than that of V_{13} (0.93 vs. 0.99, $p<0.05$). Mean positive predictive value was largest for V_{13} followed by H_{13} (Fig. 6). Pair wise comparison of Laplacian and bipolar electrodes for PPV showed no statistical difference.

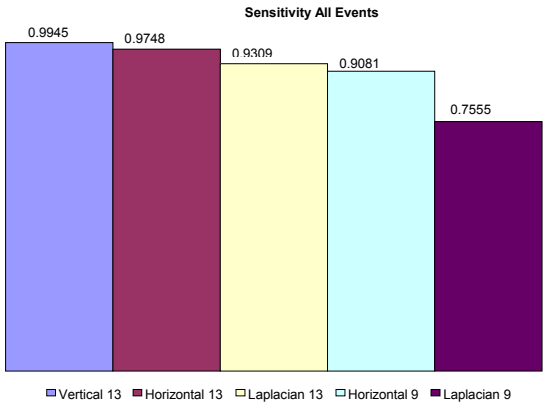

Fig. 5 Mean sensitivity over all patients and maneuvers.

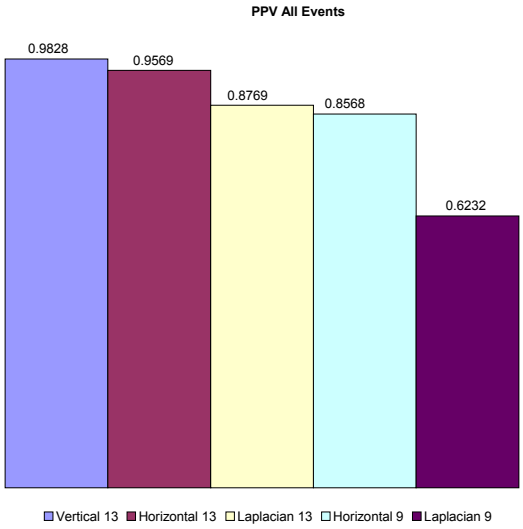

Fig. 6 Positive predictive value (PPV) over all patients and maneuvers.

IV. Discussion

This study shows, that in a patient population of adults with ICDs, Laplacian ECG recordings offer no advantage in SNR compared with standard bipolar ECG recordings. In fact, Laplacian ECGs showed reduced R-wave amplitudes (~0.10-0.20mV) compared to bipolar ECGs (~0.4-0.6mV). Wu et. al. [7] evaluated the effects of inter-electrode distance using the 5-point difference method and finds that 2-3cm spacing results in good estimates of the Laplacian ECG on the body surface. Additionally, the inter-electrode distance of the Laplacian ECG correlates with the depth at which cardiac sources are resolved. In our study, the gap between the concentric electrodes was 1.5cm which should be sufficient to resolve cardiac sources on the anterior chest assuming a 1-2cm distance to the epicardium.

During posture changes and with no challenging noise situations, the sensing performance for either bipolar or Laplacian ECG was comparable. However, under confounding myopotential noise, the sensing performance of

the Laplacian ECG quickly degraded compared to the bipolar ECG. This could be attributed to the masking of the low Laplacian R-waves (~0.1mV) by high amplitude myopotential noise resulting in oversensing issues.

Sensing performance with L_{13} on the anterior chest was better compared to that with L_9 on the lateral chest. This is expected given the localization property of the Laplacian ECG and the proximity of the heart to the anterior chest. Whereas sensitivity and positive predictive value diminished with H_9 on the lateral chest versus H_{13} and L_{13}, the change was more profound with L_9 versus L_{13} suggesting that the Laplacian ECG was more sensitive to mapping location compared to the bipolar ECG.

I. Limitations

Contact and skin impedance represent two major challenges for recording of the Laplacian ECG with concentric bipolar electrodes[6]. This is further exacerbated in the maneuvers and exercises. To circumvent this limitation we used an Ace bandage to ensure proper fixation of the Laplacian electrodes and adequate skin/electrode contact.

Sensing performance was evaluated using a sensing scheme that was initially optimized for bipolar ECGs. A different sensing scheme for the Laplacian ECGs (e.g. matched filter, different bandpass filters) may produce different results.

This study only included Laplacian electrodes with concentric circle gaps of 1.5cm. It is possible that results would differ with differing electrode gaps. Furthermore, there was no effort to optimize gaps between concentric circles to patient body mass index. Finally, due to technical difficulties and because this was a feasibility research study, only 15 patients were studied.

II. Conclusion

Because the SNR ratio on the anterior chest was comparable between the Laplacian ECG and the corresponding bipolar ECGs, and because the sensing performance for the Laplacian ECG was only marginally lower than that for the bipolar ECG, this study shows no benefit in the routine use of Laplacian ECG recordings over bipolar ECG recordings.

III. Acknowledgement

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References

[1] American Heart Association. Heart Disease and Stroke Statistics - 2003 Update. 2002, Dallas, TX: American Heart Association.

[2] Surawicz, B., Electrophysiologic basis of ECG and cardiac arrhythmias. 1995, Philadelphia: Williams & Wilkins. 622.

[3] Rudy, Y., The electrocardiogram and cardiac excitation, in Heart Physiology and Pathophysiology, N. Sperelakis, et al., Editors. 2000, Academic Press: San Diego, CA. p. 133-48.

[4] Taccardi, B., et al., Useful lessons from body surface mapping. Journal of Cardiovascular Electrophysiology, 1998. 9(7): p. 773-86.

[5] He, B. and R.J. Cohen, Body surface Laplacian mapping of cardiac electrical activity. American Journal of Cardiology, 1992. 70(20): p. 1617-20.

[6] Geselowitz, D.B. and J.E. Ferrara, Is accurate recording of the ECG surface Laplacian feasible? IEEE Transactions on Biomedical Engineering, 1999. 46(4): p. 377-81.

[7] Wu, D., H.C. Tsai, and B. He, On the estimation of the Laplacian electrocardiogram during ventricular activation. Annals of Biomedical Engineering, 1999. 27(6): p. 731-45.