

Spectral Analysis on Tripolar Laplacian Electrocardiogram

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Abstract. Tripolar Laplacian electrocardiogram (TLECG) provides high spatiotemporal distributed information about cardiac electrical activation. This study performed spectral analysis in frequency domain on four subject's body surface TLECG. The periodogram ordinates and spectral density estimates were calculated. The highest periodogram and predominant frequency of each recording location were determined by the plots of periodogram against frequency or period. Several statistics techniques were performed to test if the recorded TLECG is white noise. Kruskal Wallis analysis and Friedman's test were carried out on the highest periodogram and predominant frequencies at all recording locations. The results indicated that the highest periodogram and frequencies of the TLECG are not significantly different at different recording locations and there is no significant difference in subjects for the highest periodogram and frequency among the recording locations with 5% significant level.

1. Introduction

The human heart is a muscular organ which provides the force necessary to circulate the blood to the whole body. The heart's size is about that of a fist, and its weight is about 250–300 g. It is located in the chest between the lungs and surrounded by the pericardium. The great vessels which include the superior and inferior vena cava, the pulmonary artery and vein, as well as the aorta are located above the heart. The aortic arch lies behind the heart. The esophagus and the spine lie further behind the heart. The heart consists of four chambers: the right and left atria and

ventricles. The heart walls have three layers. The outer layer of the heart wall is the epicardium, the middle layer is the myocardium, and the inner layer is the endocardium. The heart is oriented with the right ventricle towards the anterior chest and the left atrium towards the posterior chest (see Fig. 1 (Malmivuo and Plonsey 1995)). According to the functions, the heart chamber walls have different thicknesses to assure the amount of force each chamber is required to generate. The two atria are thin-walled chambers that receive blood from the veins. The two ventricles are thick-walled chambers that forcefully pump blood out of the heart requiring higher pressure than receiving blood from the veins. Comparing the two ventricles, the left ventricular walls are much thicker than the right ventricular walls since the left ventricle needs higher pressure to pump blood to the systemic circulation than the right ventricle which provides pulmonary circulation.

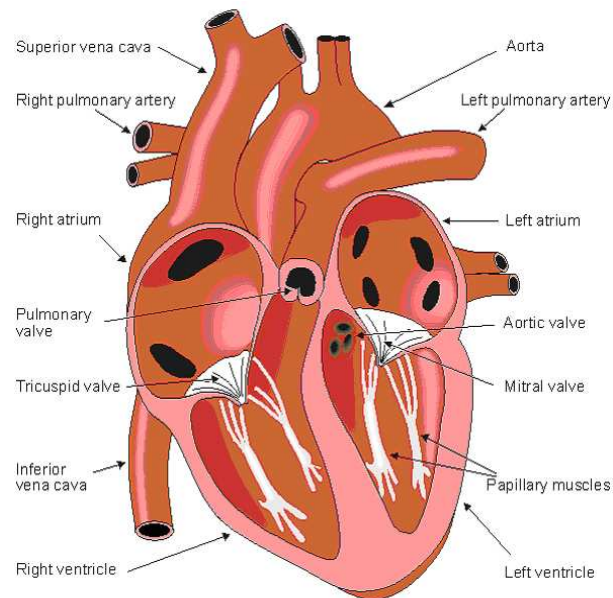


Fig. 1. The anatomy of the heart and the associated vessels (Malmivuo and Plonsey 1995).

The electrical activity of the heart can be recorded non-invasively at the surface of the body. The most commonly used clinical electrocardiogram (ECG) system, the 12-lead ECG system, consists of the following 12 leads I, II, III, aV_R , aV_L , aV_F , and $V_1 \sim V_6$, which are called the limb, augmented and precordial leads. The Laplacian is a spatial derivative of the potentials on the body surface which reduces the smoothing effect of the torso volume conduction and provides more detail in localizing and differentiating multiple concurrent dipole sources.

Tripolar Laplacian electrocardiogram (TLECG) [1], [2], a wave form that constitutes a set of observations written Y_t , where t represents time $t = 1, 2, \dots, n$, provides high spatiotemporal distributed information about cardiac electrical activation. Previous studies of TLECG [1], [2] mainly focused on the time series analysis. In time

domain the pattern characteristics of the TLECG at each time instant have been related to the underlying cardiac activation. The time lags of the TLECG at recording locations with respect to the normal Lead II ECG R-wave peak were used to perform the moment of activation map [1], [2] for time series analysis. However for the cardiac activation which has deterministic periodic components, it might be more conveniently modeled in the frequency domain in which the TLECG was broken down into periodic components. The cardiac activation frequencies on the body surface might have certain patterns which may be used for diagnosing purpose. Other researchers [3-6] used spectral analysis to investigate the periodic components in the frequency domain.

The ECG provides useful global temporal assessment of the cardiac activity, but has limited spatial information. The Laplacian electrocardiogram (LECG), which is defined as the second spatial derivative of the ECG, has been shown to be an alternative to the ECG which can be used to provide the high spatiotemporal distributed information about cardiac electrical activation, [7]. LECG was estimated using tripolar and bipolar concentric ring electrode LECG active sensors, [7-12]. Previous computer simulation and clinical experiments in [1],[2] have demonstrated that TLECG provides more detailed spatial information for the underlying cardiac electrical activation than bipolar LECG.

2. Methods

In this paper we performed a spectral analysis on body surface TLECG. The analysis was performed using SAS software package. The frequencies of the TLECG were determined and Kruskal Wallis analysis was performed on the frequencies to determine if they are significantly different at different recording locations and if the frequencies at the same location are significantly different from subject to subject.

Spectral analysis is a statistical approach that looks for periodicities or cyclical patterns in the data. In spectral analysis the finite Fourier transform is performed on the time series to decompose the data into a sum of sine and cosine waves of different amplitudes and wavelengths. The Fourier transforms decomposition of the time series Y_t is [13]:

$$Y_t = \sum_{k=1}^m (A_k \cos(\omega_k t) + B_k \sin(\omega_k t)) + e_t,$$

where Y_t is the original time series variable with n observations, m is the number of frequencies in the Fourier decomposition: $m = n/2$, if n is even; $m = (n - 1)/2$, if n is odd. A_k 's are cosine coefficients, B_k 's are sine coefficients, ω_k 's are the Fourier frequencies: $\omega_k = 2\pi k/n$ and e_t is a random error term.

Spectral analysis can be realized by the SPECTRA procedure in SAS program. The SPECTRA procedure estimates the periodogram and spectral densities. The periodogram is a volatile and inconsistent estimator of the spectrum [14]. The spectral density estimate is produced by smoothing the periodogram ordinates with a weighted moving average [14]. The cardiac signal is characterized by the recurrence of the QRS complex. This recurrence is approximately 800 ms in the healthy human heart,

namely the frequency is 1.25 Hz or 0.00125π in radians. Therefore for this study we only considered the periodogram ordinates or spectral density estimates within the frequency range from 1 Hz to 150 Hz, namely from 0.001π to 0.15π in radians. The periodicity in time series can be detected by the plots of the periodogram and spectral density against the frequency or period. The frequency of the TLECG at one recording location, namely the predominant frequency, is the one that corresponds to the highest periodogram ordinate or spectral density estimate. We subtracted the series mean before the analysis and then computed the periodogram of the series. The estimate of the spectral density of the series was computed next.

Two test statistics have been used in this paper to test whether or not a time series is white noise: Fisher's Kappa and Bartlett's Kolmogorov-Smirnov statistic [14]. The Fisher's Kappa statistic tests whether the largest periodogram ordinate can be considered different from the average of all the periodogram ordinates. Critical values for the Fisher's Kappa test can be found in SAS/ETS Software: Applications Guide 1 [15]. The Bartlett's Kolmogorov-Smirnov statistic is the maximum absolute difference of the normalized cumulative periodogram and the uniform cumulative distribution function. For $m - 1 > 100$, the critical value is $1.36(m - 1)^{-1/2}$ or $1.63(m - 1)^{-1/2}$ corresponding to 5% or 1% significance levels respectively.

The highest periodogram and predominant frequencies of body surface TLECG were determined for four subjects. It was of interest to determine whether there are significant differences in the highest periodogram and frequency among the different recording locations.

The first test used for testing the highest periodogram and frequency is the Kruskal Wallis analysis. The Kruskal Wallis analysis is a nonparametric test based on one-way ANOVA statistics. The second test used for testing the highest periodogram and frequency is the Friedman test. Friedman's test is a nonparametric test for treatment differences in a randomized complete block design. In this paper the subjects are treated as blocks. Each block of the design is a subject. The recording locations on the body surface are identified as treatments.

3. Data Analysis

Signal acquisitions were performed in accordance with the Louisiana Tech University IRB approved protocol. TLECG signals were recorded from four healthy male subjects at age 20~25. The six active LECG Tripolar concentric ring electrode sensors [1], [2] were attached inside a wide elastic strap as shown in Fig. 2a. The strap was wrapped around the body to hold the electrodes in place. A thin coat of Ten20 electrode paste (D. O. Weaver and Co, Aurora, CO, USA) was spread uniformly on the electrodes.

While recording, the subject lay in a supine position and was asked to relax and remain stationary to avoid the influence of fluctuations of the heart position on the body surface ECG and LECG [16]. The actual recordings were repeated with the active LECG Tripolar concentric ring electrode sensor array moved to each of the preplanned locations with 1.2 cm horizontal spatial sampling resolution on the chest

[1],[2]. The total 6 row by 12 column matrix body surface cardiac LECG signals were recorded for the subject from 72 locations as shown in Fig. 2b. For simplicity and consistency while referring to the LECG recording locations, we called the site in the top left corner Location 1 and the site in the bottom right corner Location 72. The rest may be deduced by analogy. For example the site in bottom left corner is Location 61.

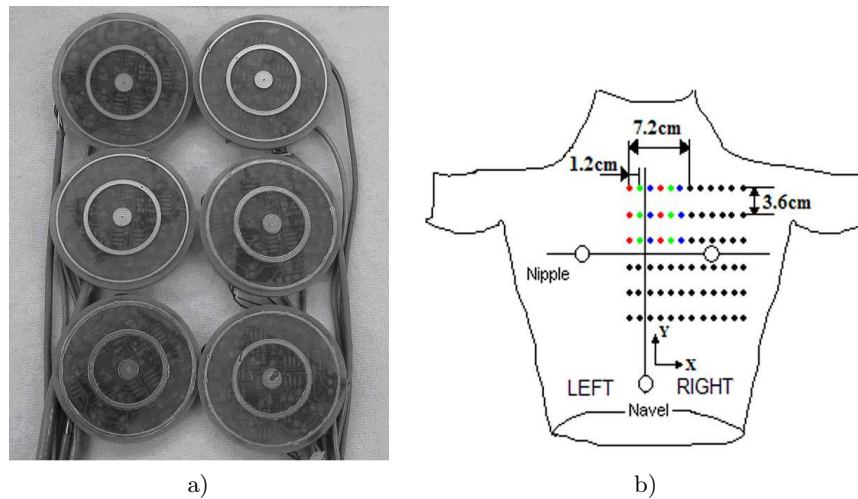


Fig. 2. a) Six active LECG Tripolar concentric ring electrode sensors configured in a 3 row by 2 column matrix and attached to the inside of a wide elastic strap; b) The 6 row by 12 column matrix of recording sites over the anterolateral chest, a frontal view. Each dot represents a recording location.

The TLECG signals were bandpass filtered with cutoff frequencies of 1 Hz and 500 Hz and recorded by a 16-bit Dataq Instruments DI-720 Series for 30 seconds. The sampling rate was 2 000 Hz for each recording location to achieve 1/2 ms resolution. Therefore, a 1600-point window covered one 800 ms cardiac cycle. In this study the first 16 000 point data which covered about 10 cardiac cycles were considered. The data for each recording location were written to an excel file with two columns. In the excel file the first column recorded the recording time instant which has 1/2 ms interval. The second column recorded the wave peak of the TLECG at the relative recording time instant. A total of 72 excel files with respect to 72 recording locations were generated for the subject.

4. Results

Figure 3 shows a segment of the TLECG from subject No. 1 at the recording Location 40. The periodic characteristic can be recognized from the plot.

Figure 4 shows the plots of the periodogram (Panel A) and spectral density (Panel B) against the frequency for subject No. 1 at recording Location 40. In Fig. 4 the ordinate shows the periodogram (a) and spectral density (b). The abscissa shows

the frequencies. As can be seen in both panels, the highest periodogram ordinate and the highest spectral density appear at the same frequency abscissa. We refer to this same frequency as the predominant frequency. It is the frequency of the body surface TLECG from subject No. 1 at the recording Location 40. By manually setting up the threshold in SAS program, the predominant frequency at Location 40 was found as 0.01021 in radians (3.25 Hz) with periodogram of 841.822 (Fig. 4a) and spectral density of 15.3572 (Fig. 4b). The white noise tests Fisher's Kappa and Bartlett's Kolmogorov-Smirnov gave a p-value less than 0.0001, which indicates that, as expected, the series is not white noise.

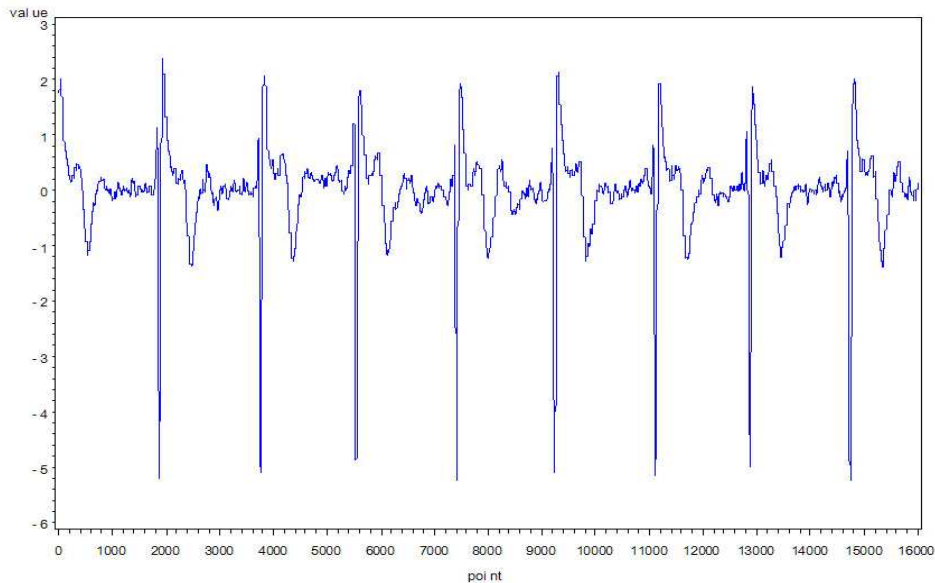
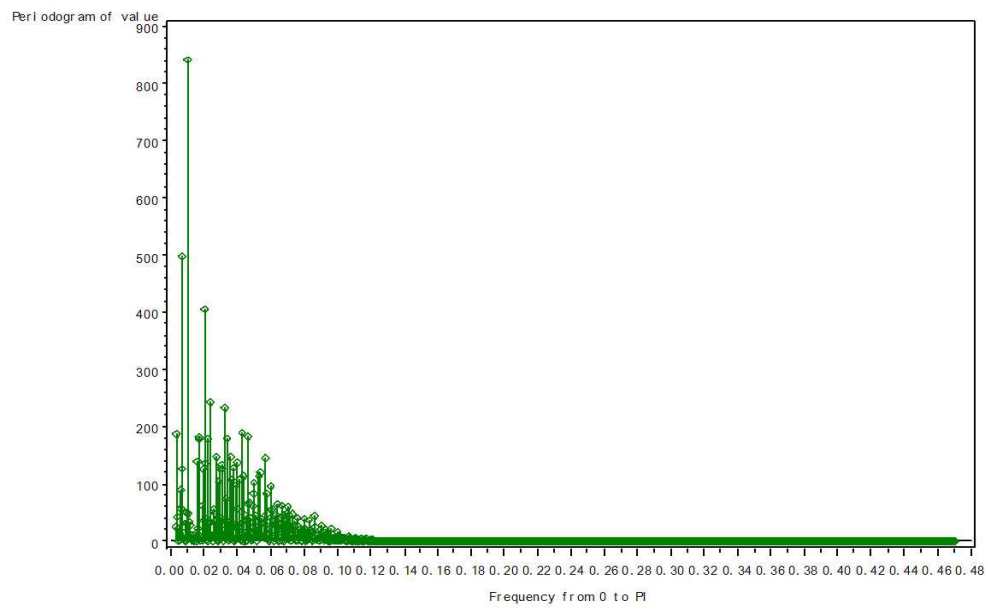


Fig. 3. A segment of the TLECG from subject No. 1 at the recording Location 40.

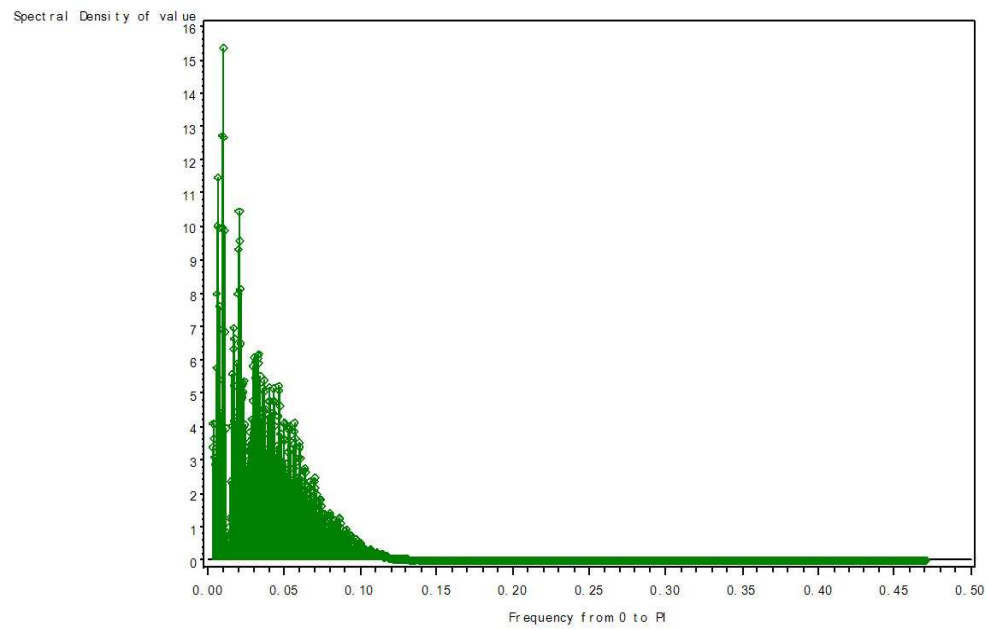
By performing the same process, the frequencies of the TLECG at all 72 recording locations were found for four subjects. Table 1 shows the frequencies of the TLECG from subject No. 1 with the mean of 2.446 Hz and the standard deviation of 1.182 Hz (2.446 ± 1.182 Hz). The first row in Table 1 shows the 12 column numbers and the first column in Table 1 shows the 6 row numbers which are used to indicate the 72 recording locations on the body surface with respect to Fig. 2b.

Table 1. The frequencies of the TLECG, from subject No. 1, at all 72 recording locations

Hz	1	2	3	4	5	6	7	8	9	10	11	12
1	2.50	1.12	3.13	1.87	2.25	0.87	3.12	2.12	2.25	2.00	2.12	1.87
2	2.50	2.25	1.12	2.50	2.25	4.25	4.00	4.12	1.37	4.00	1.25	3.25
3	1.25	1.00	1.25	2.50	2.25	2.12	2.12	3.12	2.25	3.12	1.00	4.37
4	4.37	4.63	1.88	3.25	2.25	4.37	3.37	2.25	3.37	3.37	4.50	4.50
5	1.12	4.50	4.37	2.25	1.75	4.37	3.37	1.37	1.25	3.37	1.25	1.37
6	2.13	0.88	3.25	1.12	1.00	1.00	1.62	4.00	1.00	1.12	1.00	1.12



a)



b)

Fig. 4. Plots of periodogram and spectral density against the frequency for subject No. 1 at recording Location 40.

When comparing among recording locations, the Kruskal-Wallis analysis gives the p -values for the F test as 0.2035 for the highest periodogram and 0.5007 for frequency, which indicate that the highest periodogram and frequencies are not significantly different at different recording locations. When comparing among subjects, the Kruskal-Wallis analysis gives the p -value for the highest periodogram as 0.0529, indicating that differences in subjects for the highest periodogram among the recording locations are significant at the 10% level but not at the 5% level. The p -value for the predominant frequency is 0.4685. This leads to acceptance of the null hypothesis that there is no difference for predominant frequency among subjects.

In the Friedman test, for the highest periodogram the p -value is 0.0009. Therefore, there are significant differences in the highest periodogram for different locations. The p -value of the predominant frequency is 0.5044, indicating that there is no significant difference in the predominant frequency for different recording locations. Hence, both the Kruskal Wallis and the Friedman test indicated that locations do not differ with regard to the predominant frequency.

5. Discussion

TLECG provides better spatiotemporal information than normal ECG. The interest in this study is to determine the frequency of the TLECG and determine if the frequencies at different recording locations within a subject differ significantly.

Spectral analysis was used to estimate the periodogram and spectral densities. The plots of periodogram and spectral density against the frequency show consistent results that for one recording location the highest periodogram and spectral density estimates always appear at the same frequency (Fig. 4). This predominant frequency is the frequency of the TLECG at that recording location. It is known that a healthy human has normal ECG with frequency of 1.25 Hz. The frequency of the TLECG (2.446 ± 1.182 Hz) is a little bit higher than that of the normal ECG.

The Fisher's Kappa and Bartlett's Kolmogorov-Smirnov statistics are two tests for white noise. The Fisher's Kappa test statistic of 649.2068 is larger than the 5% critical value of 7.2, so the null hypothesis that the TLECG is white noise is rejected. The Bartlett's Kolmogorov-Smirnov statistic of 0.9959704 is greater than

$$a\sqrt{1/(m-1)} = 1.36\sqrt{1/7999} = 0.015$$

for 5% significance level, so reject the null hypothesis that the spectrum represents white noise. The p values for these two tests are both less than 0.0001 which mean that these two tests' results are significant.

The Kruskal Wallis analysis is a nonparametric ANOVA test for the highest periodogram and frequency differences. The results confirmed that there is no significant difference for the predominant frequency among the recording locations. We can see a slight changing pattern of the frequencies on the body surface. For example, in Table 1, the TLECG at Locations 5, 17, 29, 41 have the same frequencies. The TLECG at Locations 2, 15, 25, 49, 64, 65, 66, 69, 70 71, 72 have similar frequencies as the normal ECG. The changing pattern of the TLECG frequency on the body surface may

depend on how the cardiac activation spreads from the heart (source) to the body surface. The source strength, source orientation and volume conduction properties determine how TLECG frequency changes on the body surface. More research needs to be performed to draw the TLECG frequency pattern on the body surface and to find the relationship between the frequency and cardiac activation.

Similar to the Kruskal Wallis analysis, the Friedman's test is a nonparametric test for location differences controlling for subjects. The results are the same for the predominant frequency that there is no significant difference for different locations. For the highest periodogram, compared to the Kruskal Wallis analysis, the Friedman's test is more sensitive. It can detect a difference at a lower significance level.

6. Conclusion

This study applied the spectral analysis on the recorded body surface TLECG data from four healthy male subjects. The frequencies of the TLECG were found to be a little bit higher than those of the normal ECG. The Kruskal Wallis analysis showed that the highest periodogram and frequencies of the TLECG at different recording locations are not significantly different and there is no significant difference in subjects for the highest periodogram and frequency among the recording locations at a lower significant level 5%. During data acquisition we recorded 72 locations on the body surface for each subject by transferring six tripolar concentric ring electrodes twelve times, which is not easy to perform and easily produce noise. The results we obtained in this study provided important theoretical foundation for simplifying the data acquisition procedure. Based on the result that there is no significant difference in frequency at different recording locations among subjects, we may be able to reduce the number of the recording locations since we will not lose any frequency information.

One only needs to be concerned about the time domain properties when one tries to reduce the number of the recording locations, which will be done in the future. The result that there is no significant difference for frequency among the recording locations guarantees that one can record the same locations for each subject. But with a higher significant level 10%, the highest periodogram will show differences for the different locations based on the individual diversity.

The human experiment in the present study is a pilot study investigating the spatiotemporal patterns of the TLECG maps from healthy male subjects using the newly designed active LECG TCE sensor. The long term goal is to provide a practical noninvasive tool for clinicians diagnosing arrhythmias and assessing the efficacy of therapy and build a periodogram data base which may be used for diagnosing purpose.

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