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Noninvasive Diagnosis of Coronary Artery Disease Using Two Parameters Extracted in an Extrema Circle of Magnetocardiogram*

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Abstract— **Magnetocardiography (MCG) is a complementary or alternative tool for noninvasive detection of coronary artery disease (CAD). The effectiveness of the tool for CAD diagnosis is generally evaluated by statistical analysis. In this study, we present a new method for screening CAD, in which two parameters including the curvature of magnetic field zero line and the area ratio of the extrema circle are extracted in magnetic field maps. 50 normal and 28 CAD subjects, whose signals were recorded by a 4-channel superconducting quantum interference device system, are analyzed with this method. The statistical results show a sensitivity and specificity of 71.4% and 72.0% respectively.**

I. Introduction

Magnetocardiography (MCG) is a noninvasive and risk-free measurement technique allowing the record of the very weak magnetic field signals generated by the electrical activity of the heart using multichannel superconducting quantum interference device (SQUID) system [1]. Magnetic field maps (MFMs) during the cardiac cycle can indirectly reflect the abnormality information of cardiac electrical activity of patients.

MCG and electrocardiography (ECG) are generated by the same electrophysiological sources and, in fact, show similar morphological features, such as the P wave, QRS complex, ST segment and T wave. However, MCG is more sensitive to tangential current while ECG is more sensitive to normal current [2]. Thus, MCG can be used as an approach complementary to ECG.

The pathological changes of the T wave are of importance for the assessment of cardiac function [3]. In recent years, increasing attention has been paid to diagnosing coronary artery disease (CAD) with MCG data in the T wave. A classification method of the current density vector maps during the ST-T interval was proposed by Hailer et al. in 2005, and the sensitivity and specificity for the diagnosis of CAD were 73.3% and 70.1% [4]. In 2007, the study of On et al. examined the usefulness of an integral MCG value of ventricular depolarization and repolarization, indicating that the average value of JTi/QRSi was significantly smaller in the CAD than in the control group [5]. In 2008, Wu et al. analyzed the two-dimensional propagation of magnetocardiographic T wave signals for characterizing myocadial ischemia, and reported the sensitivity and specificity of 74.5% and 70.0% [6]. In 2010, Kullback-Leibler (KL) entropy for the repolarization period and normalized residual magnetic field strength for the depolarization period are used in the study of Gapelyuk et al. to distinct CAD patients from the control subjects, demonstrating a high sensitivity of 88% and specificity of 88% [7].

In this study, a new method of diagnosing CAD is presented with two parameters: the area ratio of an extrema circle and the curvature of magnetic field zero line (MFZL) that extracted from MCG data in the T wave. Statistical analysis and the method evaluation are performed by using 78 sets of MCG data from the hospital. Finally, the limitation of this method is discussed.

II. Method

A. Extrema Circle of Single Current Dipole

According to the Biot-Savart law, the B_z component of the magnetic induction B recorded at the position (x_i, y_i) on the measurement plane is given as [8-9]

$$B_z(x_i, y_i) = \frac{\mu_0}{4\pi} \cdot \frac{(y_i - y_0)Q_x - (x_i - x_0)Q_y}{((x_i - x_0)^2 + (y_i - y_0)^2 + z_0^2)^{3/2}}, \quad (1)$$

where Q_x and Q_y are the components of the current dipole moment Q respectively. We have $Q_x = Q \cdot \cos\theta$ and $Q_y = Q \cdot \sin\theta$ when θ is given between Q and the x-axis. Assuming that the current dipole is located at the origin $O(0,0,0)$, the normal magnetic induction B_z is expressed as

$$A(x, y) = B_z = \frac{\mu_0 Q(y \cdot \cos\theta - x \cdot \sin\theta)}{4\pi(x^2 + y^2 + d^2)^{3/2}}, \quad (2)$$

where the depth of Q is denoted as $d = -z_0$, and $A(x, y, z)$ stands for arbitrary point on the measurement plane. Five source parameters of the single current dipole can be deduced from (1).

Here, an extrema circle is defined based on magnetic field characteristics of a single current dipole. As shown in Fig. 1, the diameter of the extrema circle equals to the distance between the local maximum and the minimum in the MFM. The distance between the extremal points M and N can be

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denoted as $D = \sqrt{2}d$, and the radius of the extrema circle is $R = D/2 = \sqrt{2}/2 \cdot d$. Thus, we have

$$x^2 + y^2 = (\sqrt{2}/2 \cdot d)^2 . \quad (3)$$

In other words, the center $O'(0,0,d)$ of the extrema circle on the measurement plane is related to the position of the current dipole while with no regard to its strength and direction.

B. *Evaluation Indices*

To detect the abnormity of cardiac electrical activity through magnetic field data, two parameters for CAD diagnosis are extracted in terms of the extrema circle concept.

1) Area ratio of extrema circle

The connection of the points where the magnetic induction equals to zero forms a piecewise magnetic field zero line (MFZL). The approximated MFZL separates the extrema circle into two parts: the magnetic induction of one part is positive and another is negative. Their area ratio can be defined as

$$L = \frac{|L_+ - L_-|}{L_+ + L_-} , \quad (4)$$

where L_+ and L_- are the areas corresponding to the positive and negative magnetic induction respectively. L is considered as a parameter for diagnosing CAD.

2) Curvature of MFZL

According to data interpolation, we assume that the magnetic induction equals to zero at points Z_1, Z_2, Z_3, Z_4 and Z_5 shown in Fig. 2. The angles between the lines which connect every two points are denoted by θ_1, θ_2 and θ_3 , respectively. The average angle of the approximated MFZL in the extrema circle is expressed as

$$\theta = \frac{1}{n}\sum_n \theta_n . \quad (5)$$

The θ is defined as the curvature of MFZL that also considered as a parameter for the estimation of CAD.

In the case of infinite homogeneous medium, MFZL is a straight line through the extrema circle center in the MFM of a single current dipole, as shown in Fig. 3(a). Thus, we have

$$L = \frac{|L_+ - L_-|}{L_+ + L_-} = 0 , \; \theta = \frac{1}{n}\sum_n \theta_n = 0 . \quad (6)$$

Theoretically speaking, the cardiac magnetic field is caused by the current density $J = J^i + \sigma E$ in myocardial tissue based on the quasistatic approximation of the Maxwell equation, where J^i is the impressed source current and σE is the Ohmic current. Therefore, the magnetic induction can be divided into two parts [8, 10-11]:

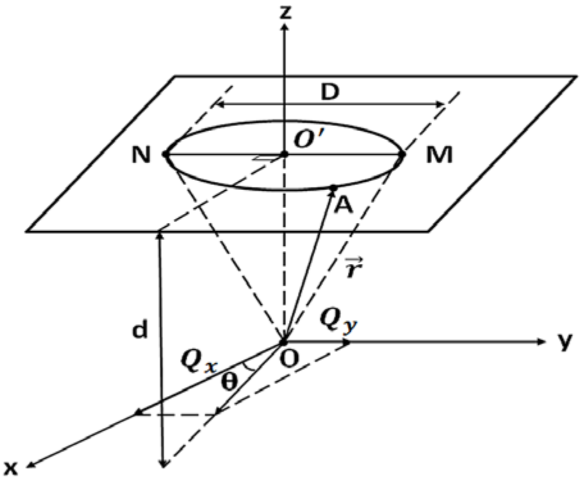

Figure 1. Sketch map of the extrema circle.

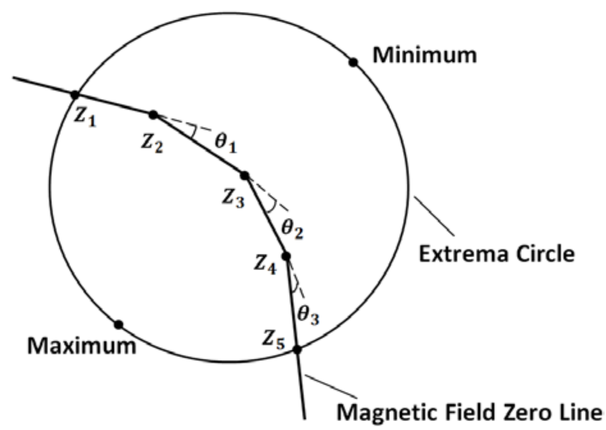

Figure 2. Sketch map of the magnetic field zero line.

$$\begin{aligned} B(r) &= \frac{\mu_0}{4\pi}\int_G (J^i(r') + \sigma E) \times \frac{r - r'}{|r - r'|^3} dv' \\ &= \frac{\mu_0}{4\pi}\int_G J^i(r') \times \frac{r - r'}{|r - r'|^3} dv' + \frac{\mu_0}{4\pi}\int_G \sigma E \times \frac{r - r'}{|r - r'|^3} dv' \quad (7) \\ &= B_\infty(r) + B_{\sigma E} \end{aligned}$$

A simulated MFM in Fig. 3(a) is generated by a single current dipole in the infinite homogeneous medium. Fig. 3(b) shows the case when $B_{\sigma E}$ is considered, where MFZL in the extrema circle is nonlinear since the presence of σE . The corresponding area ratio L and the curvature θ are also changed.

Fig. 4 shows an MFM with the MCG signals interpolated by 81×81 grid in T wave. The extrema circle area ratio L is 0.07, and the MFZL curvature θ is 0.8, indicating that volume current affects the cardiac magnetic field dramatically. Therefore, it is possible to investigate cardiac electrical activity by the two parameters L and θ of MFM.

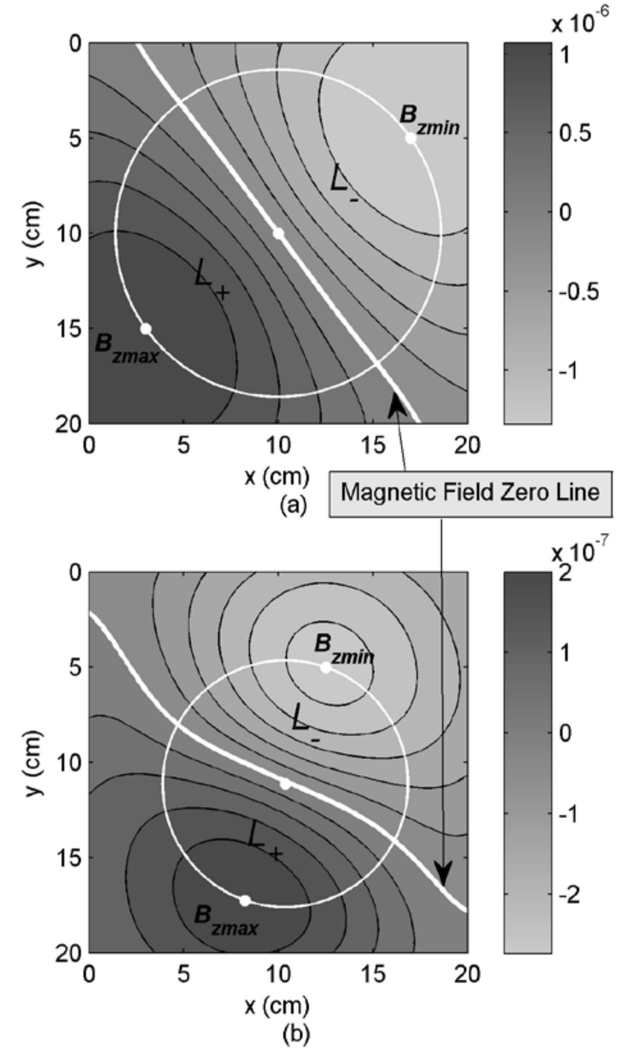

Figure 3. MFM generated by simulated single current dipole in infinite homogeneous medium (a) and the case when $B_{\sigma E}$ is considered (b).

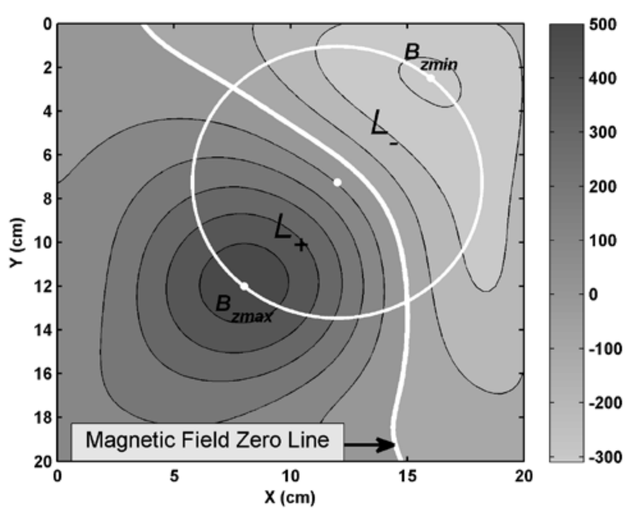

Figure 4. Curving magetic field zero line in measured MFM.

III. Application and Discussion

A. MCG Signals

The T wave signals in ECG as well as MCG reflect the electrical activity in ventricular repolarization. However, the MCG waveforms come a little earlier. The two parameters L and θ are obtained in the interval from $T_{max/3}$ to T_{max} (TT interval) of MCG signals, where the T_{max} is determined by ECG signals.

Fig. 5 reveals the two parameters calculated in a healthy subject within the 94 ms of TT interval. The area ratio L ranges from 0 to 0.1 and the curvature θ lies within 1.3-1.9. In contrast, the two parameters demonstrate larger values and wider distributions in a CAD subject shown in Fig.6. Within the 63 ms of TT interval, the parameter L lies between 0.1 and 0.5, and θ has a range of 1.5-3.7.

B. Statistical Analysis

The MCG signals from 97 subjects were recorded by four sensors arranged in a 2×2 array at nine pre-defined bed positions without a magnetically shielded room in hospital. Out of these subjects, 10 were excluded due to: 1) poor SNR and quality of the MCG and ECG signals that did not allow determining the T_{max} of the cardiac cycle; 2) the absence of local extreme value that leads to an incomplete extrema circle. Finally, 78 subjects are included in this study: 50 healthy and 28 CAD subjects, where 15 patients had single-vessel, 8 had double-vessel and 5 had triple-vessel diseases. 26 patients were documented by coronary angiography: the left anterior descending (LAD) was involved in 22, right coronary artery (RCA) in 12 and left circumflex (LCX) in 8 patients.

The maximum values of the two parameters during TT interval L_{max} and θ_{max} are statistically significant between the healthy and CAD groups with the p value of 0.0299 and 0.0001 respectively, described on the basis of Mann-Whitney U-test. It is considered that there exist cardiac abnormalities when L_{max} or θ_{max} is upper the threshold. The receiver operating characteristic (ROC) curves are used to find the best combination of the two parameters. When the thresholds are set as 0.34 for L_{max} and 2.9 for θ_{max}, the sensitivity and specificity are 71.4% and 72.0%, as shown in Table I.

Further analysis demonstrates that the two parameters are independent of the associated occluded vessels. Patients with other cardiac diseases would not be admitted by this method. The sensitivity lowers to 61.1% if 8 patients with bundle branch block are included, suggesting that the proposed method is appropriate to identify CAD.

TABLE I. Statistical Results of CAD Diagnosis

Subjects	Clinical Diagnosis Results	
	Healthy	***CAD***
Healthy	36	8
CAD	14	20

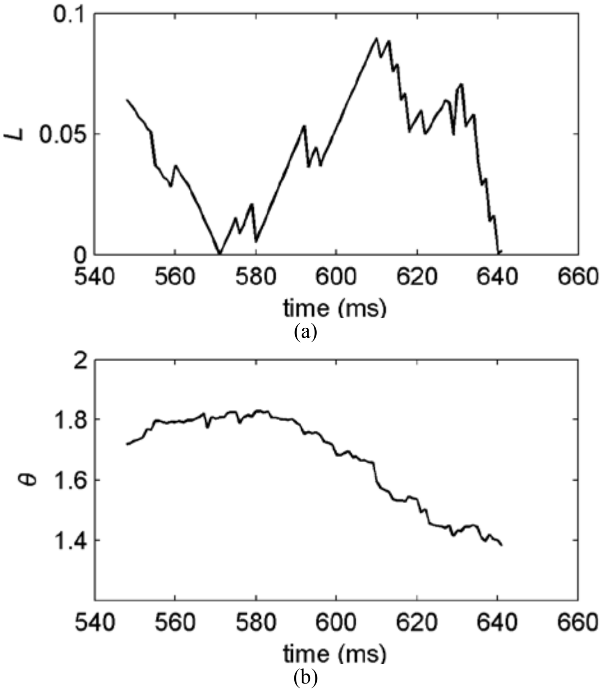

Figure 5. Area ratio L of the extrema circle (a) and curvature θ of MFZL (b) during TT interval for a healthy subject.

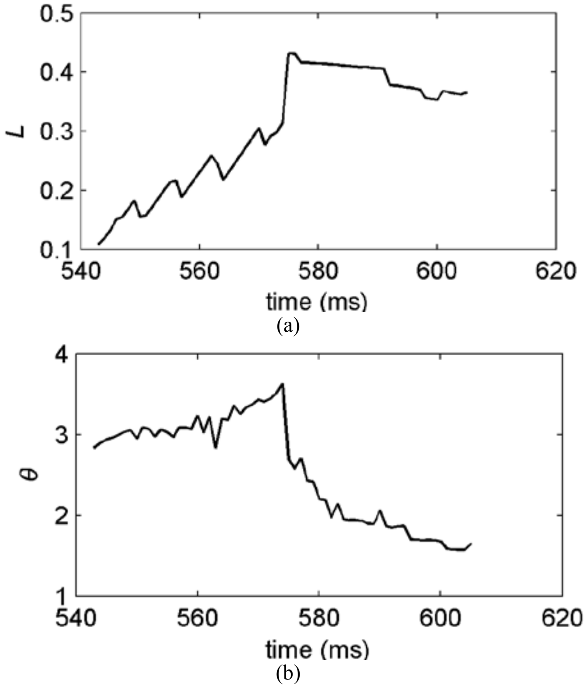

Figure 6. Area ratio L of the extrema circle (a) and curvature θ of MFZL (b) during TT interval for a CAD subject.

There are some limitations of this study. First, several MCG data are of low quality due to the record in an unshielded room, thus affects the statistical analysis. The proportion of the healthy and CAD subjects may also have an effect on the results. Second, the absence of local maximum or minimum in the MFM may limit the utilization of this method. We have shown the possibility of screening CAD patients by L and θ parameters in this method. However, a comparison of ECG and this method is not available since the lack of ECG diagnostic results. And this method needs to be further evaluated by a larger number of high quality MCG data in clinic.

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