

Imaging and Visualization of 3-D Cardiac Electric Activity

Bin He, *Senior Member, IEEE*, and Dongsheng Wu

Abstract—Noninvasive imaging of cardiac electric activity is of importance for better understanding the underlying mechanisms and for aiding clinical diagnosis and intervention of cardiac abnormalities. We propose to image the three-dimensional (3-D) cardiac bioelectric source distribution from body-surface electrocardiograms. Cardiac electrical sources were modeled by a current dipole distribution throughout the entire myocardium, and estimated by using the Laplacian weighted minimum norm (LWMN) algorithm from body-surface potentials. The estimated inverse solution of the current distribution was further improved by using a recursive weighting strategy for localized sources, such as origins of cardiac arrhythmias. Computer simulations were conducted to test the feasibility of the proposed approach by using a 3-D ventricle model embedded in a realistically shaped torso model. The boundary element method was used to solve the forward problem from assumed cardiac sources to the body-surface potentials. Two testing dipoles were placed in the left and right ventricles, simulating the early activation associated with ventricular arrhythmias. The LWMN inverse solution showed an equivalent source distribution over the entity of both ventricles, with spread areas of activity overlying the positions of the testing dipoles. The sharpened inverse image provides well-localized focal sources near the testing dipole positions. In summary, the present computer simulation suggests that the proposed 3-D cardiac current source imaging and localization approach appears to be a promising candidate for localizing and imaging sites of origins of cardiac activation.

Index Terms—Cardiac imaging, catheter ablation, electrocardiography, inverse problem, Laplacian imaging.

I. INTRODUCTION

NONINVASIVE imaging of cardiac electrical activity inside the human body has historically been an important challenge. Cardiac electrical activity is spatially distributed over three dimensions of the myocardium and evolves with time. A significant amount of effort has been put forth in past decades in the development of high-resolution cardiac electric imaging techniques, which attempt to image myocardial electrical activity without *ad hoc* assumption on the number of source dipoles [1]. Due to the high temporal resolution inherent in the bioelectric measurements such as the electrocardiogram (ECG), the availability of bioelectric source imaging modalities provides much needed high temporal resolution in mapping the functional status of the heart, and aiding clinical diagnosis and treatment such as catheter ablation of arrhythmias.

Manuscript received May 22, 2000; revised January 14, 2000. This work was supported in part by the National Science Foundation under CAREER Award BES-9875344 and by the Campus Research Board of the University of Illinois at Chicago under a grant.

B. He is with the Department of Bioengineering, University of Illinois at Chicago, Chicago, IL 60607 USA (e-mail: bhe@uic.edu).

D. Wu is with Morningstar Inc., Chicago, IL 60606 USA.

Publisher Item Identifier S 1089-7771(01)04280-7.

Efforts have been put forth on estimating the electrical potentials [2]–[10] or activation sequence [11], [12] over the epicardium from body-surface ECG measurements. Similar efforts have also been made to estimate potentials or activation sequence over the endocardium from potentials recorded over a balloon catheter [13], [14]. In these approaches, the electrical potential field or activation sequence over a part or the entire heart surface are inversely estimated with the goal to virtually “observe” cardiac electrical activity in the vicinity of electrical activity in the myocardium. Such estimation through an inverse procedure is usually called the ECG inverse solutions.

While the heart-surface inverse solutions provide much enhanced spatial resolution regarding the underlying cardiac electrical activity as compared with the smeared body-surface (or balloon surface) potential distribution, the heart-surface inverse solutions are still limited in that it is an inverse solution over the surface of the heart, within which the true myocardial electric activity is located over the three-dimensional (3-D) myocardium. For example, it is desirable to localize sites of origin of cardiac arrhythmia in the 3-D myocardium, in order to guide RF catheter-ablation procedures. The information available over the heart surface regarding the underlying myocardial activation will still need to be processed to lead to directly useful information in a clinical setting.

In this paper, we propose to image the current source distribution *inside* the 3-D myocardium from noninvasive body-surface ECG recordings, by means of a Laplacian weighted minimum norm (LWMN) algorithm. A recursive weighting strategy was further used to aid the localization and imaging of focal sources. Computer simulation studies were conducted to test the feasibility of this newly proposed 3-D source imaging approach, and are described below.

II. METHODS

A. Formulation of 3-D ECG Source Imaging

The ECG inverse problem, which shall be defined as the problem to reconstruct equivalent source distributions from body-surface electrical measurements, is intrinsically underdetermined. The source imaging method does not lead to a unique solution of the inverse problem unless further constraints are considered, e.g., the sources are restricted to the epicardium, or some physiological constraints and mathematical regularization techniques are included. Assume the electrical sources located at a small region of myocardial tissue are coherent and can be approximated by a current dipole [15], [16]. Assigning one such current dipole to each “small” region of the myocardium, we then have the following mathematical model, which relates

the current dipole distribution inside the myocardium to the body-surface ECG measurements

$$V = AX \quad (1)$$

where V is the vector consisting of m body-surface-recorded potentials, X is the unknown vector of moments of current dipoles, which are located at n sites covering the entire myocardium, and A is the transfer matrix. If we consider each point dipole consists of three components in the Cartesian coordinates, the vector X will be $3n$ in length and matrix A will be $m \times 3n$ in size. The measurement at each sensor is produced by a linear combination of all dipole components, with columns of A as weighting factors. The inverse problem of 3-D current source imaging is to seek X from V . As the number of measurement electrodes is always much less than the dimension of the unknown vector X , this problem is an underdetermined nonunique inverse problem. A proper regularization strategy is necessary for obtaining a reasonable solution to this problem.

B. Inverse Imaging Algorithms

Equation (1) is a heavily underdetermined system because, in general, the number of current dipoles inside the myocardium greatly exceeds the number of chest recording electrodes. Furthermore, there are an infinite number of solutions that may satisfy (1). The unique minimum norm (MN) solution is one of the feasible solutions [17], [18]

$$X = A^+V = A^T(AA^T)^+V \quad (2)$$

where $(*)^+$ denotes the Moore–Penrose inverse.

As the MN solution is intrinsically biased toward the superficial position, the LWMN solution has been used [19] to improve the performance of the inverse reconstruction. For LWMN [19], it utilizes a weighting operator LW , where L is a Laplacian operator and W is a diagonal $3n$ by $3n$ matrix with $w_{ii} = \|A_i\|$, and A_i is the i th column of A . Assuming the weighting factor is nonsingular, we have

$$V = A(LW)^-(LW)X \quad (3)$$

and

$$X = (WL^TLW)^-A^T(A(WL^TLW)^-A^T)^+V. \quad (4)$$

If L is simplified to be a unit matrix, (4) will be simplified to the normalized weighted minimum norm (WMN) solution. If both L and W are simplified to be unit matrix, (4) will simplify to the MN solution [16].

Furthermore, the solution resulting from the LWMN algorithm tends to be over-smoothed in the space domain because of the constraints of minimizing the Laplacian of the signal being imposed. For the purpose of localizing well-focused sources, such as the sites of origin of cardiac arrhythmias, we have applied a recursive weighting strategy, which was previously developed for improving the performance of MN magnetoencephalogram (MEG) imaging [20].

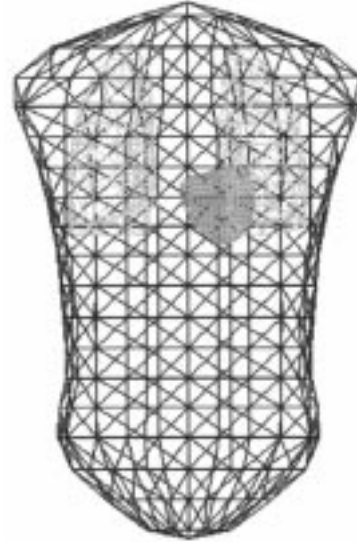


Fig. 1. 3-D heart–torso model used in the present computer simulation study. A ventricle model is embedded into a realistically shaped inhomogeneous torso. The body-surface potentials are computed by means of the boundary-element method.

The recursive weighting algorithm assumes that most of the components in the solution for localized sources will be zero, indicating no current at the corresponding locations. Equivalently, only a small number of columns of A and, hence, the corresponding elements of vector X , contribute to the measurements. The recursive weighting algorithm finds localized solutions by starting with the LWMN estimate. It then recursively enhances the values of some of the initial solution elements, while decreasing the rest of the elements until they become zeros. In the end, only a small number of winning elements remain nonzero, yielding the desired type of localized energy solution.

The numerical strategy for computing recursive solutions is the WMN, with the pseudoinverse solution given by

$$X = W(AW)^+V = WW^T A^T(AWW^T A^T)^+V \quad (5)$$

where W is an $n \times n$ weighting matrix. In each iteration step, matrix W_k is updated by taking the product of W_{k-1} with the diagonal current matrix from the preceding step

$$W_k = W_{k-1} \cdot \text{diag}(X_1^{k-1} X_2^{k-1} \dots X_n^{k-1}). \quad (6)$$

Each diagonal element of W corresponds to one element of the current. Large elements of W in conjunction with the data make the corresponding elements in X large and vice versa for small elements. From (3), we reinforce the positive (or negative) changes in the elements of X with each step. The process continues until most elements are reduced to zero. Therefore, the solutions are localized and the spatial resolution is enhanced.

C. Simulation Procedures

A 3-D heart–torso inhomogeneous volume conductor model [21] was used in the present simulation study (Fig. 1). There are 511 nodal points in total over the torso surface and lung surfaces. Considering the low conductivity of the lungs, the conductivity ratio of torso to lungs was set to 1 : 2 [1], [15]. The conductivity for cardiac muscle is assumed to be the same as the torso. The

ventricles were divided into an equidistant lattice structure with 6.7 mm between nodes. In total, there are 1124 voxel nodes in the 3-D solution space of the ventricles.

The body-surface potentials generated by current sources somewhere inside the inhomogeneous volume conductor are given by [22]

$$\phi(\vec{r}^*) = \frac{1}{\sigma_1} \phi_\infty(\vec{r}^*) - \frac{1}{4\pi} \sum_{i=1}^N \frac{\sigma_i^+ - \sigma_i^-}{\sigma_1} \int_{S_i} \phi(\vec{r}) d\omega \quad (7)$$

where \vec{r}^* is any observation point inside the volume conductor, ϕ_∞ is the potential at the same point in an infinite medium with unit conductivity, and σ_i^+ and σ_i^- are the conductivities of the medium just outside and inside S_i , respectively. Note that all homogeneous compartments are bounded by surfaces $S_1 \dots S_N$ of arbitrary shape, and S_1 is the outer surface of the volume conductor.

Two current dipoles, oriented from the waist toward the neck, were used to approximate well-localized myocardial electrical sources. Gaussian white noise of 5% was added to the calculated body-surface potentials from assumed cardiac sources to simulate noise-contaminated body-surface ECG measurements. The 3-D equivalent cardiac source distribution was then estimated by means of the LWMN algorithm with recursive weighting strategy.

III. RESULTS

Fig. 2 illustrates an example of 3-D cardiac electric imaging of two dipole sources located close to the anterior epicardium at the right and left ventricles. The locations of the dipoles are illustrated in Fig. 2(c) by the red color, where the green color refers to zero activity. The LWMN solution is illustrated in Fig. 2(a), where the red and yellow colors illustrate the strength of the equivalent dipole source distribution throughout the ventricles. Fig. 2(a) shows that the LWMN solution reached maxima in the regions overlying with the locations of the two source dipoles. However, the source distribution is widely spread over a large volume of the ventricles due to the smoothing constraints introduced in the LWMN solution. The recursively weighted LWMN solution is illustrated in Fig. 2(b), where, after 20 iterations, the source strength distribution is well focused at three locations: two of the source localization results being consistent with the “true” dipoles, and one extra “false” source position on the posterior ventricular wall introduced by the inverse imaging procedure.

Fig. 3 illustrates another example of 3-D cardiac electric imaging of two dipole sources located close to the endocardium at the right and left ventricles [see Fig. 3(c)]. The LWMN solution is illustrated in Fig. 3(a), where the red and yellow colors illustrate the strength of the equivalent dipole source distribution through the ventricles. Fig. 3(a) shows that, when the two dipoles were located close to the endocardium, the LWMN solution reached a maximum in the right ventricle, overlying with the location of the source dipole. However, the source strength distribution showed a small local maximum in the left ventricle, with a strength much weaker than the maximum at the right ventricle. This bias toward the right

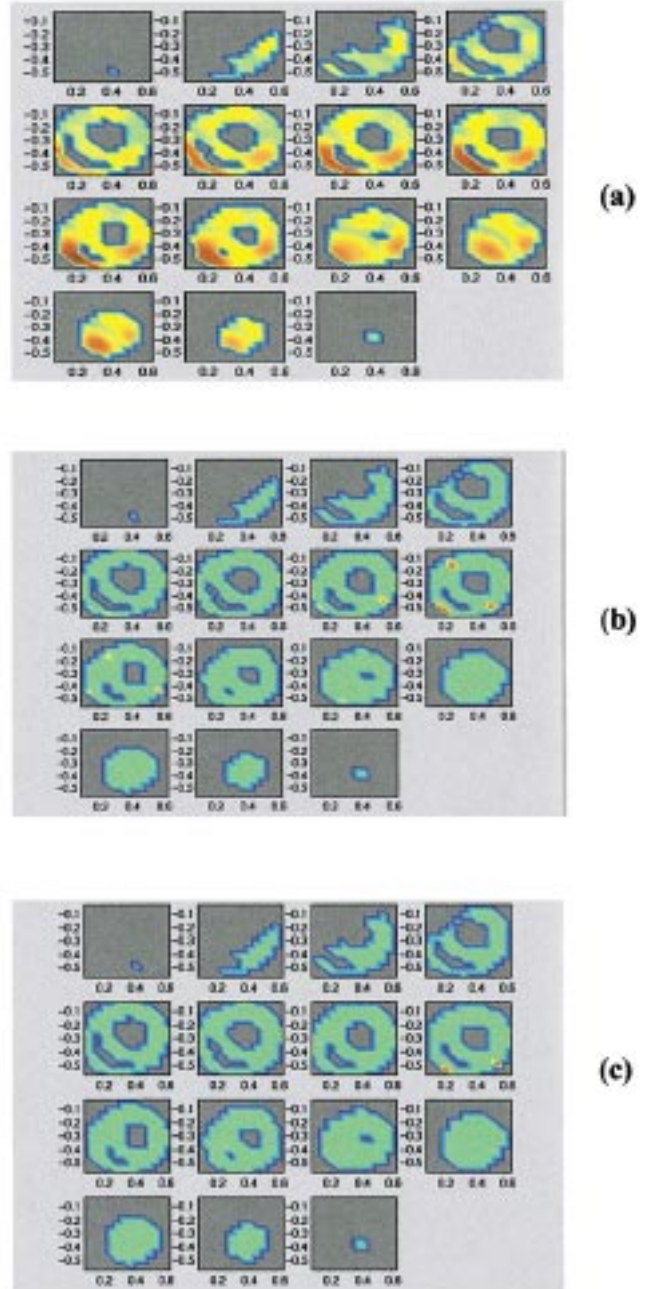


Fig. 2. Example of 3-D cardiac electric source imaging of two dipole sources located close to the anterior epicardium at the right and left ventricles in (c). The LWMN solution is illustrated in (a), where the red and yellow colors illustrate the strength of the equivalent dipole source distribution over the ventricles. The recursively weighted LWMN solution is illustrated in (b). The 15 small panels starting from the left- to the right-hand side (and from the top to the bottom) illustrate the source strength distribution over 15 slices of the ventricles (from base to apex).

ventricular activity may be due to the increased distance from the left ventricular endocardium to the chest, as compared with the distance from the right ventricular endocardium. Similar to the epicardial dipoles, the reconstructed LWMN solution was widely spread over a large volume of the ventricles, due to the smoothing constraints introduced in the LWMN solution. The recursively weighted LWMN solution is illustrated in Fig. 3(b), where, after 20 iterations, the source strength distribution is

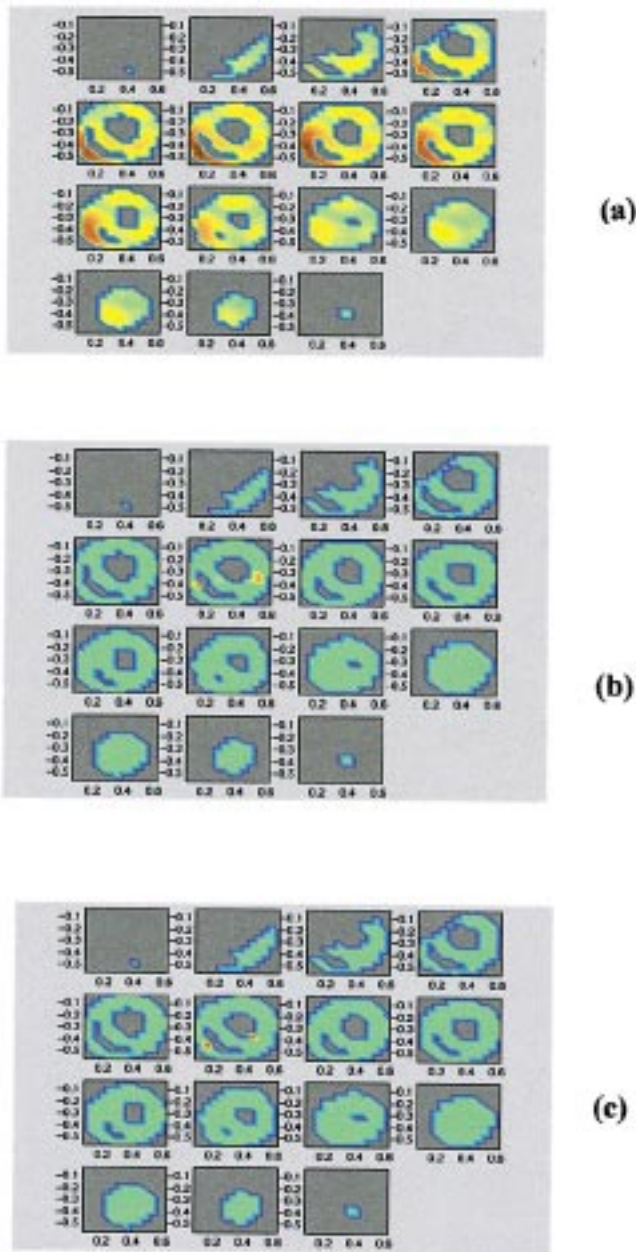


Fig. 3. Example of 3-D cardiac electric source imaging of two dipole sources located close to the endocardium at the right and left ventricles in (c). The LWMN solution is illustrated in (a), and the recursively weighted LWMN solution is illustrated in (b). The 15 small panels starting from the left- to the right-hand side (and from the top to the bottom) illustrate the source strength distribution over 15 slices of the ventricles (from base to apex).

well focused at two locations: one of the source localization results being consistent with the “true” dipole at the right ventricle, and another being located at the left ventricular endocardium, shifted 1 cm left of the “true” dipole position.

Fig. 4 illustrates another example of 3-D cardiac electric imaging of two dipole sources located close to the endocardium at the right ventricle and the epicardium at the left ventricle [see Fig. 4(c)]. The LWMN solution is illustrated in Fig. 4(a), where the red and yellow colors illustrate the strength of the equivalent dipole source distribution throughout the ventricles. Fig. 4(a) shows that the LWMN solution reached maxima in both the right ventricle and the left ventricle, overlying with the

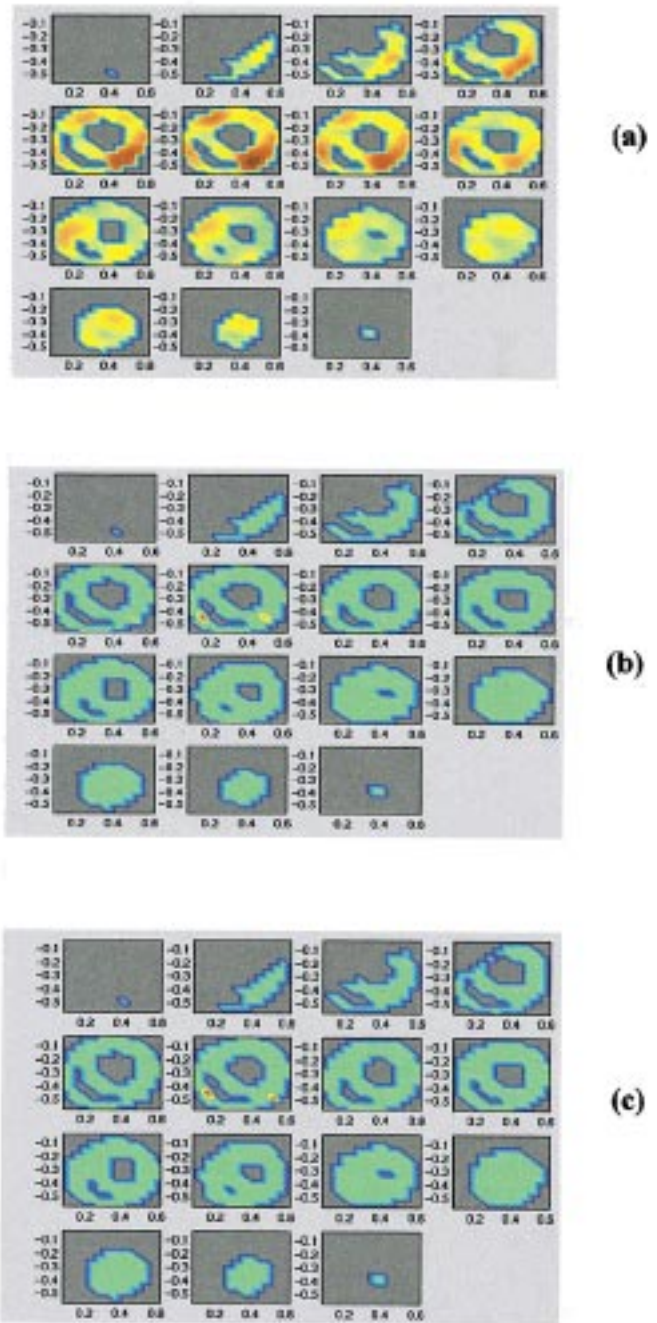


Fig. 4. Example of 3-D cardiac electric imaging of two dipole sources located close to the endocardium at the right ventricle and the epicardium at the left ventricle in (c). The LWMN solution is illustrated in (a), and the recursively weighted LWMN solution is illustrated in (b). The 15 small panels starting from the left- to the right-hand side (and from the top to the bottom) illustrate the source strength distribution over 15 slices of the ventricles (from base to apex).

locations of the source dipoles. The LWMN solution showed a stronger source distribution over the left ventricle as compared with that in the right ventricle, probably due to the fact that the dipole in the left ventricle is located closer to the chest, as compared with the dipole located in the right ventricle. In addition, Fig. 4(a) shows that there is another major area of activity appearing over the posterior ventricular wall in the LWMN solution. The recursively weighted LWMN solution is illustrated in

Fig. 4(b), where, after 20 iterations, the source strength distribution is well focused at two locations: one of the source localization results being consistent with the “true” dipole at the right ventricle, and another being located at the left ventricle, shifted 1 cm toward the direction of endocardium from the “true” diople position in the left ventricle.

IV. DISCUSSION

Noninvasive localization and imaging of sites of origin of supraventricular and ventricular arrhythmias is of great importance for guiding RF ablation procedures. Of importance is to develop reliable and fast imaging techniques, which can identify the sites where the ablative energy is to be delivered. Investigators have used various mapping procedures to aid localization of sites of origin of cardiac arrhythmias, including endocardial activation mapping [23], electromagnetic–anatomical mapping [24], and pace mapping [25]. However, due to the significant period of time required by these clinical mapping procedures, the application of RF ablation procedures for treatment of ventricular arrhythmias has remained limited. Thus, it is highly desirable to be able to fast localize and image sites of origins of ventricular arrhythmias.

Historically, numerous efforts have been made in an attempt to noninvasively localize and image cardiac electrical activity from body-surface ECG signals [1]. A number of investigators have studied electrocardiographic inverse solutions, which attempt to mathematically reconstruct the equivalent source distribution of cardiac bioelectrical activity. Cardiac electrical sources have been modeled by a single dipole [26] and multiple dipoles [26]–[29], multipoles [30], heart-surface isochrone [11], [12], or epicardial potentials [2]–[10]. For the clinical applications to localize the sites of origin of arrhythmias, 3-D information is desirable. The equivalent dipole solutions were among the early ECG inverse solutions. It has been shown that the single equivalent moving dipole solution can provide good approximation of the myocardial electrical activity if only one small area of the myocardial tissue is activated at a time [26]. Previous studies have also shown that the equivalent dipole solution suffers from existing experimental noise if the number of the moving dipoles increases to two or more [29]. In a clinical setting, one wishes to localize and image sites of origin of arrhythmias, which are generally unknown. Therefore, there is a need to develop a technique, which can localize and image sites of origin of cardiac arrhythmias without *a priori* constraints on the number of equivalent moving dipoles (such as one).

In this paper, we have proposed to image and localize cardiac electrical activity in the 3-D myocardium by using the LWMN algorithm with a recursive weighting strategy. In our proposed approach, we do not attempt to make assumptions on the number of focal cardiac sources. In other words, we do not assume the sources associated with body-surface ECGs to be one or two dipoles. The *a priori* information we have taken into account in our 3-D cardiac electric imaging approach is that the myocardial electrical activation is smooth over a reasonably small region, and that the sites of origins of cardiac arrhythmias are localized over small regions inside the myocardium, which is consistent

with experimental observations during the early phase of ventricular tachycardia [31]. In our computer simulation studies, we have initially tested, for the first time, the feasibility of our approach using the LWMN solution with a recursive weighting strategy in localizing and imaging well-localized cardiac electric activities in a 3-D heart–torso model.

While the present simulation results appear to be encouraging, there are a few open questions to be addressed in future studies. First, as Fig. 2 shows, the present imaging algorithm sometimes introduces a spurious solution in a region where there is no actual source. Therefore, the imaging results should be interpreted as candidate sites of origins of cardiac arrhythmias and the final decision should be made based on catheter measurements. With efficient computation based on spontaneous body-surface ECG distribution, the imaging results can be promptly screened by inserting the catheter toward the region where a candidate solution is suggested. Such spurious solutions can be excluded by examining the catheter recordings. Since sites of origin of arrhythmias that need RF intervention do not have a large number in a clinical setting, such spurious solutions may not introduce significant problems. Second, the current LWMN solution with a recursive weighting strategy still show a certain shift toward the “interior” of the myocardium from the “true” solution positions (Figs. 3 and 4). Both the LWMN algorithm and the recursive weighting algorithm may contribute to such a “shift.” Compared with other available methods to localize sites of origin of cardiac arrhythmias, the present results of 1-cm accuracy appear to be promising and encouraging. Third, in order to systematically evaluate the performance of the proposed approach to image and localize focal cardiac sources, a more thorough study should be conducted by evaluating the reconstruction results of a number of source configurations including sources located in various regions of the heart with various orientations. Nonetheless, the LWMN solution with recursive weighting strategy appears to be a promising candidate for localizing and imaging sites of origin of cardiac activation.

ACKNOWLEDGMENT

The authors are grateful to J. Lian, University of Illinois at Chicago, for useful discussions and D. Yao, University of Illinois at Chicago, for assistance of programming.

REFERENCES

- [1] R. M. Gulrajani, *Bioelectricity and Biomagnetism*. New York: Wiley, 1998.
- [2] R. C. Barr, M. Ramsey, III, and M. S. Spach, “Relating epicardial to body surface potential distributions by means of transfer coefficients based on geometry measurements,” *IEEE Trans. Biomed. Eng.*, vol. BME-24, pp. 1–11, Jan. 1977.
- [3] C. P. Frazzone, B. Taccardi, and C. Viganotti, “An approach to the inverse calculation of epicardial potentials from body surface maps,” *Adv. Cardiol.*, vol. 21, pp. 50–54, 1978.
- [4] R. D. Throne and L. G. Olson, “A generalized eigensystem approach to the inverse problem of electrocardiography,” *IEEE Trans. Biomed. Eng.*, vol. 41, pp. 592–600, June 1994.
- [5] B. He, “On the Laplacian inverse electrocardiography,” in *Proc. Ann. Int. IEEE Eng. In Med. Biol. Soc. Conf.*, 1994, pp. 145–146.
- [6] F. Greensite and G. Huiskamp, “An improved method for estimating epicardial potentials from the body surface,” *IEEE Trans. Biomed. Eng.*, vol. 45, pp. 98–104, Jan. 1997.

- [7] B. He and D. Wu, "A bioelectric inverse imaging technique based on surface Laplacians," *IEEE Trans. Biomed. Eng.*, vol. 44, pp. 529–538, July 1997.
- [8] P. R. Johnston, "The Laplacian inverse problem of electrocardiography: An eccentric spheres study," *IEEE Trans. Biomed. Eng.*, vol. 44, pp. 539–548, July 1997.
- [9] P. R. Johnston and R. M. Gulrajani, "A new method for regularization parameter determination in the inverse problem of electrocardiography," *IEEE Trans. Biomed. Eng.*, vol. 44, no. 1, pp. 19–39, Jan. 1997.
- [10] H. S. Oster, B. Taccardi, R. L. Lux, P. R. Ershler, and Y. Rudy, "Noninvasive electrocardiographic imaging: Reconstruction of epicardial potentials, electrograms, and isochrones and localization of single and multiple electrocardiac events," *Circulation*, vol. 96, pp. 1012–1024, 1997.
- [11] J. J. M. Cuppen and A. van Oosterom, "Model studies with inversely calculated isochrones of ventricular depolarization," *IEEE Trans. Biomed. Eng.*, vol. BME-31, pp. 652–659, Oct. 1984.
- [12] F. Greensite, "Demonstration of 'Discontinuities' in the time derivatives of body surface potentials, and their prospective role in noninvasive imaging of the ventricular surface activation map," *IEEE Trans Biomed Eng.*, vol. 40, pp. 1210–1218, Dec. 1993.
- [13] Z. W. Liu, P. Jia, P. R. Ershler, B. Taccardi, R. L. Lux, D. S. Khoury, and Y. Rudy, "Noncontact endocardial mapping: Reconstruction of electrograms and isochrones from intracavitary probe potentials," *J. Cardiovasc. Electrophysiol.*, vol. 8, pp. 415–431, 1997.
- [14] D. S. Khoury, K. L. Berrier, S. M. Badruddin, and W. A. Zoghbi, "Three-dimensional electrophysiological imaging of the intact canine left ventricle using a noncontact multielectrode cavitory probe: Study of sinus, paced, and spontaneous premature beats," *Circulation*, vol. 97, pp. 399–409, 1998.
- [15] R. Plonsey and R. C. Barr, *Bioelectricity—A Quantitative Approach*. New York: Plenum, 1988.
- [16] B. He, D. Yao, and D. Wu, "Brain electric imaging," in *Advances in Electromagnetic Fields in Living Systems*, J. C. Lin, Ed. Norwell, MA: Kluwer, 2000, vol. 3, pp. 73–120.
- [17] M. Hamalainen and R. Ilmoniemi, "Interpreting measured magnetic fields of the brain: Estimates of current distributions," Helsinki Univ. Technol., Helsinki, Finland, Tech. Rep. TKK-F-A559, 1984.
- [18] B. Jeffs, R. Leahy, and M. Singh, "An evaluation of methods for neuromagnetic image reconstruction," *IEEE Trans. Biomed. Eng.*, vol. BME-34, pp. 713–723, Sept. 1987.
- [19] R. D. Pascual-Marqui and R. Biscay-Lirio, "Low resolution electromagnetic tomography: A new method for localizing electrical activity in the brain," *Int. J. Psychophysiol.*, vol. 18, pp. 49–65, 1994.
- [20] I. F. Gorodnitsky, J. S. George, and B. D. Rao, "Neuromagnetic source imaging with FOCUS: A recursive weighted minimum norm algorithm," *Electroenceph. Clin. Neurophysiol.*, vol. 95, pp. 231–251, 1995.
- [21] D. Wu, H. C. Tsai, and B. He, "On the estimation of the Laplacian electrocardiogram during ventricular activation," *Ann. Biomed. Eng.*, vol. 27, pp. 731–745, 1999.
- [22] A. C. L. Barnard *et al.*, "The application of electromagnetic theory to electrocardiology II: Numerical solution of the integral equations," *Biophys. J.*, vol. 7, pp. 463–491, 1967.
- [23] J. K. Friedman, K. J. Jenkins, S. D. Colan, R. V. Praagh, J. E. Lock, and E. P. Walsh, "Multipolar endocardial mapping of the right heart using a basket catheter: Acute and chronic animal studies," *Pacing and Clin. Electrophysiol.*, vol. 20, pp. 51–59, 1997.
- [24] L. Gepstein, G. Hayam, and S. A. Ben-Haim, "A novel method for non-fluoroscopic catheter-based electroanatomical mapping of the heart: *in vitro* and *in vivo* accuracy results," *Circulation*, vol. 95, pp. 1611–1622, 1997.
- [25] A. SippensGroenewegen, H. Peeters, E. Jessurum, A. C. Linnenbank, E. O. Robles de Medina, M. D. Lesh, and N. M. van Hemel, "Body surface mapping during pacing at multiple sites in the human atrium," *Circulation*, vol. 97, pp. 369–380, 1998.
- [26] R. M. Gulrajani, F. A. Roberge, and P. Savard, "Moving dipole inverse ECG and EEG solutions," *IEEE Trans. Biomed. Eng.*, vol. BME-31, pp. 903–910, MONTH 1984.
- [27] D. M. Mirvis, F. W. Keller, R. E. Ideker, J. W. Cox, R. J. Dowdie, and D. G. Zettergren, "Detection and localization of multiple epicardial electrical generators by a two-dipole ranging technique," *Circulation Res.*, vol. 41, pp. 551–557, 1977.
- [28] J. de Guise, R. M. Gulrajani, P. Savard, R. Guardo, and F. A. Roberge, "Inverse recovery of two moving dipoles from simulated surface potential distributions on a realistic human torso model," *IEEE Trans. Biomed. Eng.*, vol. BME-32, pp. 126–135, Feb. 1985.
- [29] Y. Okamoto, Y. Teramachi, and T. Musha, "Limitation of the inverse problem in body surface potential mapping," *IEEE Trans Biomed Eng.*, vol. 30, pp. 749–754, Nov. 1983.
- [30] D. B. Geselowitz, "Multipole representation for an equivalent cardiac generator," *Proc. IRE*, vol. 48, pp. 75–79, 1960.
- [31] D. P. Zipes and J. Jalife, Eds., *Cardiac Electrophysiology—From Cell to Bedside*, 2 ed. Philadelphia, PA: Saunders, 1995.



Bin He (S'87–M'88–SM'97) received the Ph.D. degree in bioelectrical engineering (with highest honors) from the Tokyo Institute of Technology, Tokyo, Japan.

He completed his Post-Doctoral Fellowship in biomedical engineering at Harvard University and the Massachusetts Institute of Technology (MIT), Cambridge. He remained with MIT as a Research Scientist. In 1994, he joined the faculty of the University of Illinois at Chicago, where he is currently an Associate Professor in bioengineering and electrical engineering, and the Director of the Biomedical Functional Imaging and Computation Laboratory. His major research interests include functional biomedical imaging, neural engineering, cardiovascular engineering, and computational biomedicine. He has been active in editorial activities, including being the editor of the Kluwer Academic/Plenum Book Series on "Bioelectric Engineering," and guest editor for *Critical Reviews in Biomedical Engineering*, *Methods of Information in Medicine*, and *Electromagnetics*. He is listed in *Who's Who in Science and Engineering*, *Who's Who in America*, and *Who's Who in the World*.

Dr. He has been a guest editor for the *IEEE Engineering in Medicine and Biology Magazine*. He was the recipient of National Science Foundation CAREER Award, American Heart Association Established Investigator Award, and The University of Illinois University Scholar Award.

Dongsheng Wu received the B.S. and M.S. degrees in electrical engineering from Tsinghua University, Beijing, China, in 1992 and 1994, respectively, and the Ph.D. degree in bioengineering from the University of Illinois at Chicago, in 1998. Her doctoral dissertation concerned the forward and inverse problems of electrocardiography.

She is currently with Morningstar Inc., Chicago, IL.