Optimization of Right Ventricular Conductance Catheter Configurations Using Finite Element Modeling and Direct Search Algorithms

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ABSTRACT

Catheter curvature can affect accuracy of conductance volume measurement, especially with complex geometries such as the right ventricular chamber. In order to evaluate reduction in volume measurement error with the use of conductance catheter configurations with optimized curvature, we present results from using direct search algorithms to find the optimal curvature and electrode distribution in the right ventricle. It was found that there is an apparent increase in accuracy with curvature (down to zero percent volume error), owing to greater linearity in the region of field which was farther from the exciting electrodes. Optimal curvature and number of electrodes depended on the ratio between an extreme point (*ep*) distance (representing the degree of curvature) and a source point (*sp*) distance (representing half the distance between source and sink), and also with the position of the first and last measurement electrodes.

Keywords: Conductance catheter; Direct search algorithm; Catheter curvature optimization; Right ventricular volume

1. INTRODUCTION

There are many current methods that have been developed to measure ventricular volume. These methods may be classified as: angiography, echocardiography, sonomicrometry, radionuclide ventriculography, magnetic resonance imaging (MRI), and conductance catheterization [1-10]. Imaging techniques, based on mathematical modeling or geometric approximation, such as angiography and echocardiography may be invalidated by pathologically induced changes in ventricular geometry [1-3]. Sonomicrometry can provide accurate right ventricular volume by increasing the number of piezoelectric transducers, but this method's application has been limited as requiring an open-chest preparation for transducer placement [4]. MRI, using tomography and numerical techniques, is able to derive right ventricular volume. However, continuous real-time volume measurement such as beat-to-beat changes cannot be assessed by this method due to long processing times [6-7].

Bulky electronics and power consumption are another factor which should be considered in right ventricular volume assessment with implantable system. Techniques used to take an image in methods, such as echocardiography, sonomicrometry, and magnetic resonance imaging, usually use bulky electronics and power consumption which unavoidably preclude to implanted application [3-4,6-7]. However, this obstacle does not happen to conductance catheterization.

Conductance catheterization also has advantages in enabling measurement of intra-ventricular blood volume in continuous real-time monitoring and may potentially find application in implanted cardiac output monitoring [8-10]. This ability would be valuable in assessing right ventricular function although application to right ventricle volume measurement has up to now been precluded by the anatomic complexity of the right ventricular chamber leading to relatively large volume measurement error using this technique, of up to 50% or more.

Although the conductance catheter is a realistic candidate for continuous real-time right ventricular volume measurement in implantable system, one of obstacles which precludes this ability is non-uniform electric potential field distribution from a point source. We have previously used analytical and numerical techniques to investigate the electric potential field distribution in a uniform conductor with both single and dual excitation at asymmetrical positions [11-12]. Results show that the electric potential field distribution from using point current excitation is non-uniform. This can lead to an underestimation of true volume.

For this paper, the aim is to present optimization of right ventricular conductance catheter configurations in a non-uniform field using realistic ventricular geometry. Due to the crescent shape of the right ventricle, a straight conductance catheter will

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not span the whole chamber. As a result, use of a curved catheter is the preferred choice. However, different catheter curvatures can affect accuracy of volume measurement due to the non-uniform electric potential distribution from a bipolar source [13]. Thus, the question arises as to whether it may be possible to find an optimal curvature for achieving accurate volume measurement.

Previous workers [14] have used correction factors to calibrate measurement results, achieving a volume error of 7%. These factors were empirically found by a complex algorithm to compensate for the nonlinear relation between conductance and true ventricular volumes, based on the distance from the excitation electrode and catheter curvature. Nevertheless, the assumptions of this correction have little theoretical basis, and the parameters for the nonlinear relation were not clearly defined. Investigation of curved catheter configurations and use of optimization methods have not yet been reported for this application.

Here we present finite element models of the realistic right ventricle to explore electric potential field non-uniformity from a bipolar source. Also, optimization using a pattern search algorithm to find optimal catheter curvature and electrode distribution for a conductance catheter is the objective of this paper.

2. METHODOLOGY

2.1 Conductance Technique Theory

A model of a curved conductance catheter, divided into segments, in a ventricle is shown in Fig. 1. The model consists of the catheter, source and sink electrodes, measurement electrodes, the ventricular wall, and the blood within the ventricle. Constant electric current was injected through the source and sink electrodes, and the segmental resistance was calculated knowing the potential drop across each volume segment [15] as follows:

$$R_i = \frac{\rho L_i}{A_i} = \frac{\rho L_i^2}{A_i C_i} \frac{\rho L_i^2}{VoL_i} \quad (1)$$

where R_i segmental resistance, ρ=resistivity, L_i effective spacing between electrodes, A_i cross sectional area of the segment and Vol_i=segmental volume.

Effective spacing was defined as the distance between adjacent measurement electrodes in the $\vec{a}_N$ direction (Fig.2),

$$Effective\ spacing(i) = \left(\vec{L}c_i - \vec{L}c_{i-1}\right) \cdot \vec{a}_N \quad (2)$$

where $Effective\ spacing(i)$ = segmental effective spacing, and $\vec{L}c_i$ the vectors between adjacent measurement electrodes directed along the curved catheter as shown in Fig. 2. Use of effective spacing improved the accuracy of the volume calculation [13].

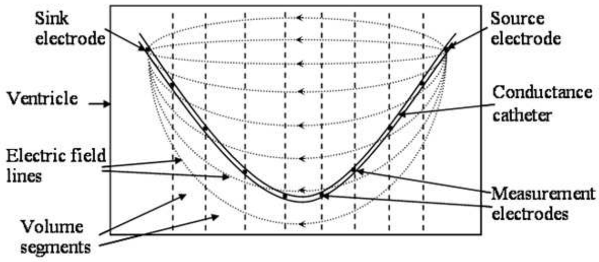


Fig.1: *Model of a conductance catheter inserted into the model*

An expression for segmental volume may be found from (1),

$$Vol_i = \frac{\rho L_i^2}{R_i} \quad (3)$$

Knowing the segment volumes, we can find the total ventricular volume, Vol_{total},

$$Vol_{total} = \sum_{i=1}^{p} Vol_i, \quad (4)$$

where p =total number of volume segments.

2.2 Intra-cardiac Conductance Sensors

The conductance catheter configuration presently used in most studies is a straight catheter with 8, 10, or 12 electrodes and a closed-end pigtail (Fig. 3) [16]. Platinum electrodes are used, and interelectrode spacing varied to accommodate a range of applications with the length of catheter depending on heart size. However, some researchers have modified an original straight line conductance catheter to a curved conductance catheter to measure blood volume within the right ventricle [13,14]. A conductance catheter may also incorporate a semi-conductor pressure transducer at the distal end to simultaneously measure pressure as well as volume [17].

2.3 Conductance Catheter Configurations

In practice, a curved catheter can be introduced into the right ventricular chamber by passing through the right atrium and exiting into the pulmonary artery, as in [10]. Three positions, current source, current sink, and Extreme position were used to configure the curved catheter (Fig. 2). The Extreme position was the point on the catheter that was the furthest distance from the axis ($\vec{a}_N$) joining the current sink and source positions and was also constrained to be at the middle between the sink and source. Cubic spline interpolation was used to define the curve of the catheter from these three points [18]. Electrodes were distributed as determined from optimization.

2.4 Finite Element Modeling and Solution

The right ventricular model (Fig. 4) was constructed from raw geometry data from the "Auckland model" of the canine heart [19]. The data consisted of a high density of points defining the right ventricular myocardium in 3D. Geometric volume was constructed by first interpolating these original data points to create outlines and then these outlines were used to create small surfaces to construct the right ventricular model. This procedure was achieved by Boolean operations using commercial software (ANSYS, Inc., Canonsburg, USA). Then, the right ventricular solid entity was meshed using tetrahedral solid elements, and Poisson's equation (5) was solved for source and sink electrodes represented by individual nodes.

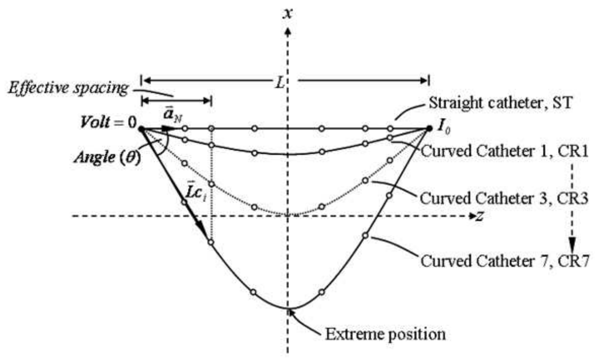


Fig.2: *Configurations of conductance catheter curvature (the example shows 6 measurement electrodes)*

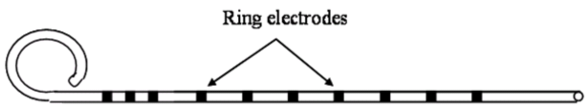


Fig.3: *The configuration of a conductance catheter*

$$\nabla^2 V = -I/\sigma \quad (5)$$

where blood conductivity (σ) was 0.67 S/m [20], and boundary conditions consisted of an applied current (I) of 20 μA. on a specified node (representing source electrode) and a constraint by a voltage of zero on another specified node (representing sink electrode). A Finite Element solution was found using ANSYS 10 multi-physics software running on a 2.80 GHz PC

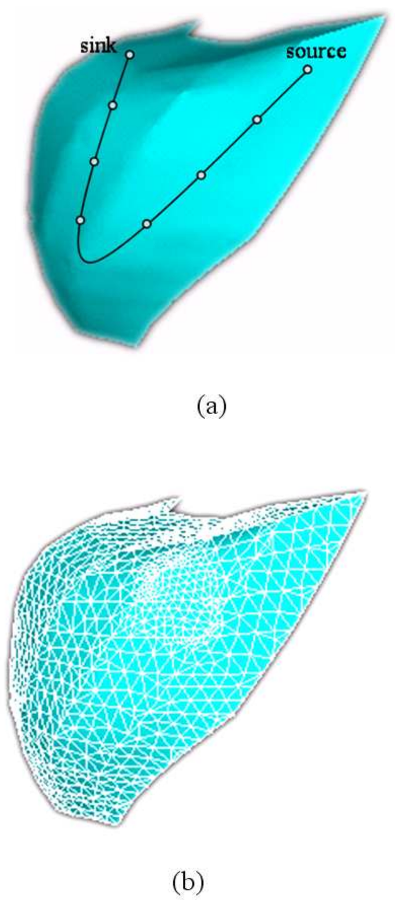


Fig.4: *Realistic right ventricular models (a) Sink and source electrodes in a realistic right ventricle (b) Meshed model*

under windows XP. The resulting electric potential values (V) were substituted into (3). Then, equation (4) was used to find the segmental volumes and the total volume within the region of the right ventricle spanned by the measurement electrodes.

Numerical accuracy of the Finite Element model was ensured using progressively refined meshes with a high node concentration around the source and sink until change of calculated conductance volumes was small.

Note that use of this isolated right ventricular model may cause to limit the room for inserting a conductance catheter into the right ventricle. Also, the electric potential field distribution was typically confined within a limited region [21]. For example, in case of including other surrounding structures such as the left ventricle, the electric field may radiate beyond the right ventricle into the left ventricle (parallel conductance).

2.5 Pattern Search Algorithm to Optimize Catheter Design

A pattern search algorithm was used to solve for optimal catheter curvature and electrode distributions, using MATLAB and the Pattern Algorithm Toolbox (Mathworks, Massachusetts, USA). Catheter configurations were optimized by varying the position of the measurement electrodes along the catheter and also the catheter's Extreme position.

The percent true volume error (ε_t) was used as the value function for the standard Pattern Search Algorithm method [22]. The optimization method involved calculation of this value for initial locations of chosen measurement electrodes, with the optimum location being the first configuration satisfying the optimal value function.

A summary of the optimization method follows, with further details in Fig. 5. First, discrete data such as node numbers, element numbers, and nodal potential values were transferred from the Finite Element model. Then, for each calculation, the procedure involved the following steps. Measurement electrode locations and the position of extreme point were chosen. Solid angle theory [23] was then used to identify which elements from the Finite Element model enclosed the catheter measurement electrodes. Then, quadratic interpolation was used to interpolate the element nodal potential values to obtain values for the measurement electrode potentials. Conductance volumes were then determined for different measurement electrode configurations, and ε_t calculated by comparing with the finite element true volume of the right ventricle. If this value satisfied the value function, then processing was stopped; otherwise, the procedure was repeated.

3. RESULTS

The results presented in this paper are from one of our case studies. As a result, only one resulting electric potential field pattern within the right ventricular model is shown in Fig. 6 owing to use of only one exciting electrode configuration. High and low potential regions corresponding to the closest locations to the source and sink can be clearly seen. Owing to the irregular shape of the right ventricle, asymmetry in the field distribution can be seen between the source and sink electrodes.

Percent true volume error (ε_t) for variations in the extreme position and the number of measurement electrodes is in Fig. 7. Three different plots are shown in Figs. 7(a)-(c), corresponding to three different positions of the first and last measurement electrodes relative to the exciting electrodes (the current source and sink).

Fig. 8 shows an example of optimal distributions of measurement electrodes on the catheter with different values of extreme position. The location of the eight measurement electrodes is clearly shown for catheter configurations ST and CR1-CR6. Nevertheless, for CR7, optimal measurement electrode distribution was found using only four discrete positions.

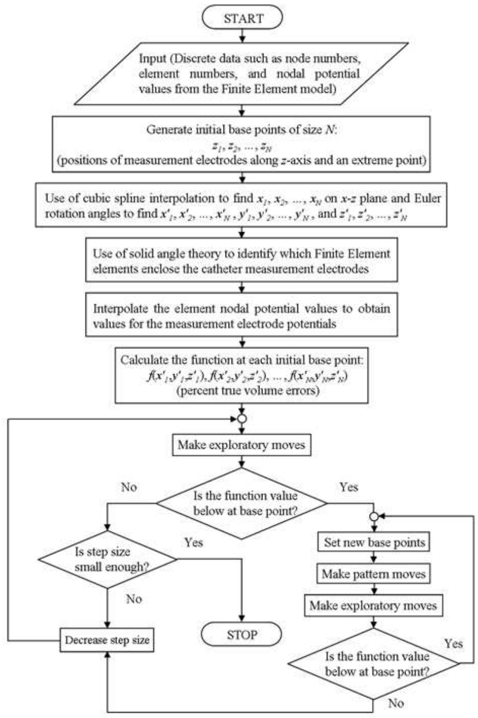


Fig.5: *The Pattern Search Algorithm method used for optimizing percent true volume error (ε_t) using conductance catheter techniques*

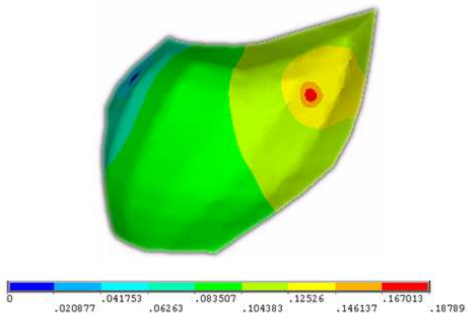


Fig.6: *The electric potential field pattern within the right ventricular model*

4. DISCUSSION

The electric potential field pattern in Fig. 6 shows that the field radiates from the current source and sink. The contour lines of the field pattern show the potential gradient is very high near the current source and sink and decreases relatively between them. Furthermore, due to a point current source, the electric potential field distribution is non-uniform and becomes more uniform with distance from source and sink.

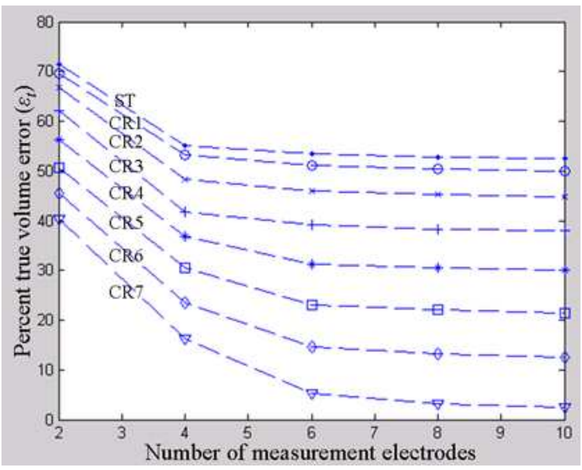
Results from Fig. 7 show that overall there is a progressive decrease in volume error with increasing catheter curvature and also as the number of measurement electrodes is increased.

However, using more than eight measurement electrodes results in little improvement in volume error. Furthermore, when the positions of the first and last measurement electrodes are moved farther from the exciting electrodes, volume error may not decrease when using extremely curved catheters such as CR7 in Fig. 7(c). That means optimal catheter curvatures depend on the ratio between an extreme point distance (representing the degree of curvature) and a source point distance (representing half the distance between source and sink), and also with the position of the first and last measurement electrodes. For example, optimal catheter curvature for Figs. 7(b) and (c) is CR7 and CR6, respectively. Note that only four measurement electrodes gave effectively zero percent true volume error for CR7 in Fig. 7(b).

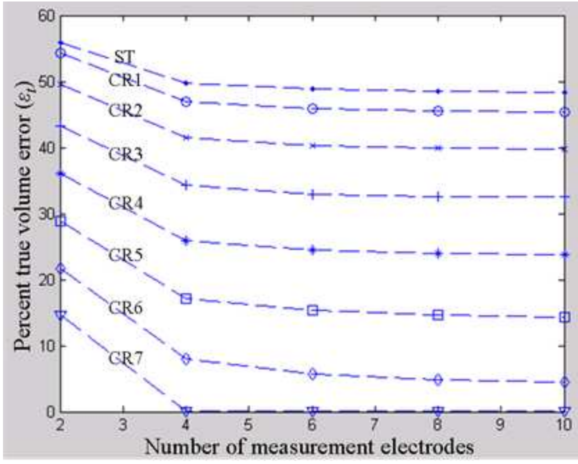
Optimal electrode distributions in Fig. 8 shows that using equally spaced measurement electrodes is not ideal for achieving the most accurate volume measurement. Moreover, optimization of measurement electrode positions result in higher electrode densities closer to the source and sink electrodes (the regions where the electric potential field is most non-uniform).

The apparent increase in accuracy with curvature is therefore most likely due simply to the consequently greater linearity of the field in the region of the measurement electrodes.

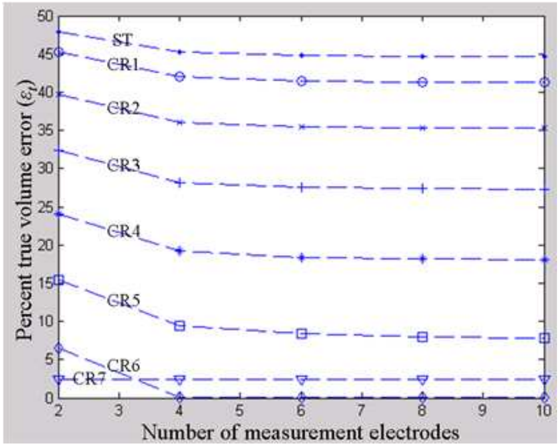
Similarly, for a particular curvature, the increase in accuracy achieved by an unequal distribution of measurement electrodes over the length of the catheter is likely to be due to the better representation of the field achieved by having more closely spaced electrodes in the regions of the greatest non-linearity.



(a)



(b)



(c)

Fig. 7: *Percent true volume error (ε_t) versus number of measurement electrodes for the right ventricular model with variation in the extreme position: (a) the closest position; (b) an intermediate position; and (c) the farthest position of the first and last measurement electrodes from the exciting electrodes*

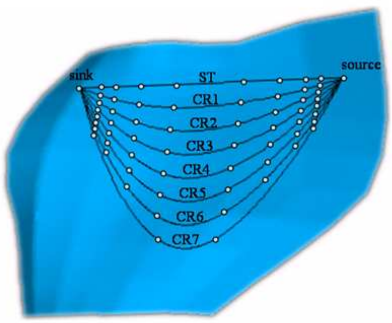


Fig. 8: *The catheter configurations with optimal electrode distributions within the right ventricle of eight measurement electrodes*

5. CONCLUSION

Optimizing catheter curvature and measurement electrode distribution by using a Pattern Search algorithm with Finite Element modeling is able to improve the accuracy of conductance catheter volume measurement. As a result, use of curved catheter configurations results in more accurate measurement of conductance volume than use of a standard straight configuration for the model used in this study. Also, for optimal catheter curvature, only four measurement electrodes may be used to achieve a zero percent true volume error.

6. ACKNOWLEDGMENT

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