Translation of Body Surface Maps Between Different Electrode Configurations Using a Three-Dimensional Interpolation Scheme [1]

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Introduction

While standard electrocardiography has benefited immensely from the comparison of data recorded in different laboratories, the inherent incompatibility among BSPM leadsets has precluded quantitative comparison. Within each lab, interpolation, approximation, and estimation are routinely used to generate maps on two-dimensional grids, allowing comparison and pooling of data from different patients[1, 2]. In general, however, this comparison has been limited to maps recorded with the same lead configuration and not between research labs using different leadsets. Furthermore, such reconstructions are fraught with systematic distortion errors since each involves projecting the locations of the recording electrodes, locations in three-dimensional space, onto a two-dimensional representation of the torso.

The goal of interpolation is to estimate the value of an unknown function at any location, based on knowledge of only a limited sampling of data representing that function. In BSPM, interpolation provides a means of drawing isocontours from a finite set of values recorded at more or less standard locations. While the science of interpolation has yet to provide completely general-purpose methods for interpolating functions of three dimensions[3], if interpolation is restricted to a subset of three-dimensional space defined by a surface, there are schemes available. One such scheme, actually a representative of a family of related techniques, suitable for BSPM data has been reported in the literature by Oostendorp *et al.*[4]. The concept underlying this approach is that it is possible to define a local approximation of some well chosen function of the sampled data and use this function to *constrain* the distribution in some global sense. The global constraint determines the approximate values at locations for which there is no recorded data.

The instrumented, electrolytic torso tank offers unique experimental conditions for addressing many questions in electrocardiology. Sources as simple as a single bipole and as complex as a perfused, beating heart can be placed in the tank and the resulting potential distributions sampled on the tank surface and throughout the volume conductor. For the results described here, we used a fiberglass tank in the shape of a child's thorax into which we suspended a Langendorff-perfused dog heart. The resulting torso potential distributions formed the complete data set against which we could compare the results of interpolation from selected lead subsets. In order to evaluate the robustness of the interpolation algorithm to different activation sequences and potential distributions, we paced the heart from five widely spaced epicardial sites, one atrial and four ventricular.

The goal of this research was to evaluate an interpolation technique with which we hope to be able to pool BSPM data from collaborating laboratories. To this end, we have defined a common torso geometry and mapped both the University of Utah (CVRTI) 192-electrode[1] and the Dalhousie University 117-electrode[2] leadsets to this geometry. We took subsets of

[1]From Electrocardiology '93: Proceedings of the International Congress on Electrocardiology, XXth Annual Meeting, P.W. MacFarlane, editor, pages 179–182. World Scientific Press, Singapore, 1993

the recorded torso tank data corresponding to both leadsets and used them to estimate the complete 658-lead common torso geometry distributions. The results have left us confident that it is, indeed, possible to transform data between these two leadsets and thus pool body surface maps recorded from both.

Methods

Interpolation: The interpolation scheme we have implemented is based on an approach described in detail by Oostendorp *et al.*[4] and consists of two steps. The first involves describing the geometry of the surfaces over which we will interpolate the measured data and then mapping each recording electrode site to a node in this geometry. The common geometrical model for this work was derived from a torso-shaped electrolytic tank containing 370 recording electrodes on the surface supplemented by a further 288 measured locations, for a total of 658 nodes. 192 of the recording electrodes corresponded to the standard lead system used at the CVRTI[1].

The second component of the scheme is the interpolation itself. The core of the interpolation algorithm is a discrete approximation for a function of the surface data, in this particular case, the second order spatial gradient, or Laplacian. The numerical value of the Laplacian at any point on the surface characterizes its smoothness, with smaller values suggesting more smoothness. One way to approximate the Laplacian of a function f at the point x_0, a node of the geometrical model, is as

$$\nabla^2 f(x_0) \approx \frac{4}{\overline{h}} \left(\frac{1}{n} \sum_{i=1}^{n} \frac{f_i}{h_i} - \overline{(\frac{1}{h})} f(x_0) \right) \tag{1}$$

where ∇^2 is the symbol for the Laplacian operator, h_i is the distance between x_0 and its i^{th} neighbor, $\overline{h}$ is the mean distance to all n neighbors, and $\overline{(1/h)}$ is the mean of the inverse distance to all n neighbors (see Figure 1(B)). The interpolation procedure based on this formulation consists of applying equation (1) to each node in the geometry to generate a set of weighting coefficients, then dividing the geometry into nodes with known (measured) values and those for which we wish to estimate values. By adjusting the unknown values so that the Laplacian over the whole surface is minimized (which reduces to the least squares solution of a well conditioned, overdetermined linear system), we can generate a complete set of values for all nodes in the geometry.

Experiments: To test the interpolation scheme, we recorded potentials from the surface of the electrolytic tank, into which we suspended a perfused dog heart (see Figure 1(A)). The recording system sampled up to 256 channels simultaneously at 1 kHz and for the 370-lead tank, a relay network provided switching between two banks of electrodes for asynchronous recording. A set of 5 leads common to each bank contained the necessary information for subsequent alignment of the data. We selected from five different epicardial sites (1 atrial, 4 ventricular) for pacing at a cycle length of 350 ms.

We then applied the interpolation scheme to the potential distributions recorded from the torso tank by selecting subsets of recording electrodes. In one set of simulations the goal was to reproduce the original recorded signals from random subsets of varying number of leads. In another simulation, we computed the potentials for the complete, 658-node common torso geometry from the 370 recorded leads and from the 117- and 192-lead subsets. The

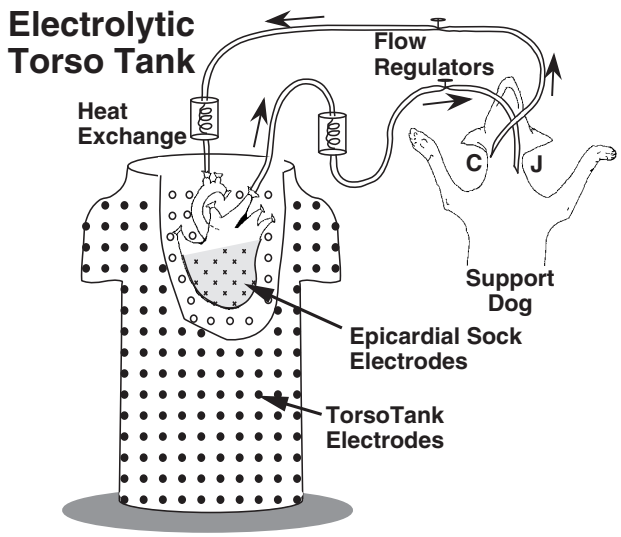

Figure 1: (A) Electrolytic torso tank and perfused heart prepration and (B) schematic of the interpolation neighborhood near a point in the geometry.

statistical measures used to compare results in each case were correlation coefficient and RMS, relative, and maximum errors averaged over a single beat.

Results

The results of the interpolation process, expressed via the correlation coefficient between recorded and interpolated data, from random subsets of the 378 recording electrodes for one pacing site are shown in Figure 2. Acceptable results were obtained with as few as 115 electrodes, although several of the other merit curves showed a marked break in this region, indicating that further reduction in lead number would produce large reconstruction errors.

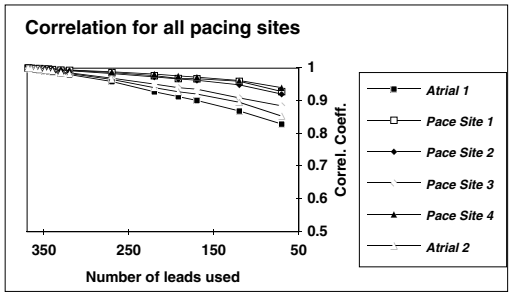

Figure 2: Correlation coefficient as a function of lead number for Laplacian interpolation scheme.

A comparison of the maps interpolated on the complete common torso geometry from 378, 192, and 117 leads of input data taken for a single instant 60 ms into the QRS is shown in Figure 3. These and similar results over the entire QRST reveal that all the relevant features of the map, location of extrema and zero-line, general contour shape, *etc.,* are well

reproduced when we use any of the 370-, 117- and 192-lead subsets as the starting point of the interpolation.

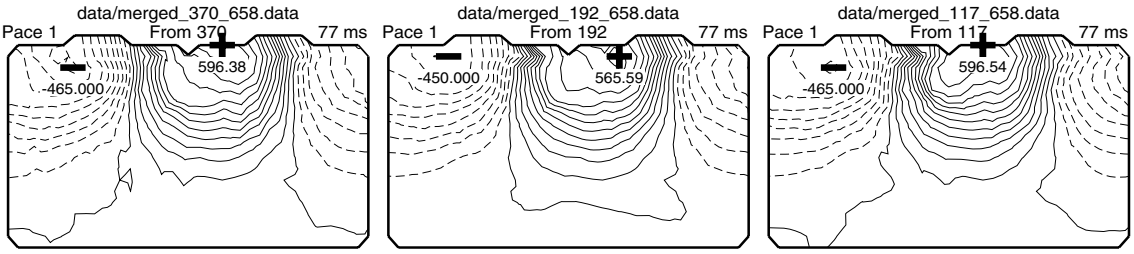

Figure 3: Isopotenial maps for an instant in time from direct tank measurements (A), interpolation from 192 leads (B), and interpolation from 117 leads (C). Contours are 50 μV.

Discussion

It should be noted that the interpolation method described here can easily be generalized to functions other than the Laplacian (second order spatial gradient). One might, for example, employ the first order spatial gradient as the constraint, and minimize it globally, or even regionally, perhaps based on some physiologic constraints on the spatial frequency of the distribution. Also, while the proposed use of this technique lies in the interpolation of the electric potential, there is no inherent reason why any other quantity cannot be handled in the same way.

A unique feature of this interpolation scheme is that it depends only on the *geometry* of the lead locations and underlying torso geometry, and not on the information content or any characteristic of the data being recorded. This results in a very general purpose scheme which does not require a large database of existing maps, nor should it be sensitive to pathologies which occur infrequently in such databases. The scheme also takes into account, in a direct way, the true three dimensional nature of the objects being sampled and hence can avoid some of the errors of two-dimensional interpolation schemes.

The reason that this scheme could easily be adapted to translating BSPM data from one electrode scheme to another, is that both the CVRTI and the Dalhousie systems provided approximately similar *coverage* of electrodes, even though their spacing and layout differed. Similar coverage makes it fairly straightforward to map electrode schemes onto the common geometry, and also ensures that we remain largely in the domain of *interpolation* and need seldom resort to *extrapolate* to match lead systems. Hence standard coverage defines a rather modest constraint imposed on a lead system designer, while providing a pathway for compatibility between existing and future systems.

One weakness of any scheme that represents individualized data on a common geometry lies in the assumption that the geometrical transformation does not distort the true spatial distributions in ways that could alter interpretation of the data. Body surface mapping and, indeed, electrocardiography in general, assume that it is possible to place leads on locations of the body *relative* to common anatomical locations and, thus reduce sensitivity to differences in torso shape and size. The true effects and limitations of these assumptions will perhaps come to light with the ongoing research in understanding the nature of the transfer of electrical information from the heart to the torso surface.

In the meantime, each mapping group defines some sort of common lead geometry and uses it to compare maps from different patients. We have extended this approach and combined it with a sophisticated, three-dimensional interpolation scheme, to link different lead systems to a common, realistically shaped torso geometry. We are now using the technique to pool relatively scarce BSPM recordings of transient ischemia produced by coronary angioplasty from three different research labs.

References

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