Is Accurate Recording of the Surface Laplacian Feasible?

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Abstract: Experimental and model studies were performed to measure the surface Laplacian using a rectangular finite difference approximation. The experimental approach used 10 normal subjects with two sites on the torso. Electrode spacing was 2 cm. The surface Laplacian is theoretically independent of rotation of the electrode array. The data showed considerable variation with rotation. Model studies employed a realistic 23 dipole source. A spherical volume conductor showed invariance with rotation, as anticipated theoretically. A realistic torso, however, showed variation with rotation, although a not as severe as that measured. The average signal to noise ratio was 3.3 and 2.5 at the two sites. These results raise serious questions about the practical ability to measure the surface Laplacian on the torso.

INTRODUCTION

The use of the surface Laplacian, L, for skin potentials was first proposed by Hjort [1] for studying the electroencephalogram and later by He et al [2] for the electrocardiogram. One rationale is that **L** will give different and perhaps more localized information concerning the sources which give rise to the surface potential distribution, V. It has also been proposed that use of **L** rather than the potential will enhance the solution of the inverse problem.

On a flat surface $\mathbf{L} = \partial^2 V/\partial x^2 + \partial^2 V/\partial y^2$ where x,y are the Cartesian coordinates of a point on the surface. As an approximation,

$$L(x,y) \approx \frac{V(x+d,y)+V(x-d,y)+V(x,y+d)+V(x,y-d)-4V(x,y)}{d^2}$$

which can be measured by an array of 5 electrodes where d is the distance from the center electrode to each of the other 4 electrodes. This approximation is valid for a sphere provided that d is interpreted as the distance along the surface of the sphere.

The surface Laplacian is invariant with respect to a rotation of axes. Therefore the measurement should not change significantly with a rotation. In practice, a variation might be observed because of the curvature of the surface and the finite separation, d. Such variation would indicate inappropriateness of the flat surface approximation.

METHOD

Surface Laplacian recordings were obtained using a five electrode array. Recordings were taken from 10 subjects, using a grid spacing of 2cm. The subjects were normal males in the age range of 20-32 years. Two locations were used, one to the left of the center of the chest and one near the left shoulder. An electrode template was cut out of a thin sheet of flexible plastic. Self adhesive Ag/AgCl electrodes (Graphic Controls model 5500 Q-Trace Gold) were placed over each of the five holes on the template to form the electrode array.

For each recording location, two recordings were taken, one with the y axis of the electrode grid oriented in the head to foot direction, and one with it rotated 45°. Approximately one minute of data was recorded for each recording location and orientation. Each data set consisted of four difference voltages together with their average, which is proportional to the surface Laplacian.

Four differential amplifiers and a multi-channel analog to digital converter (BIOPAC MP100A) connected to a computer were used. The center electrode was connected to the negative input of each amplifier. Each of the peripheral electrodes was connected to the positive input of an amplifier. The outputs of the four amplifiers were averaged using a resistor network. This analog average agreed with a digital one obtained subsequently. The amplifiers had a low frequency cutoff of 0.05 Hz, and a high frequency cutoff of 1 KHz. The individual potentials and their average were recorded. The MP100A had a resolution of 16 bits, a range of ±10 volts, and a sampling rate of 3237.29 Hz.

In several instances severe problems with 60 Hz noise were encountered. To remove the noise, digital filtering was performed on the signals after they had been recorded. The recordings were first passed through a 60 Hz notch filter, and then though a 100 Hz lowpass filter. The recordings which were noise free were also run though this series of filters, and then compared to the unfiltered signal to insure that the filters were not causing any distortion of the signal.

The recordings were analyzed for noise content. A signal averaging technique was used to separate the signal from the noise. A window just enclosing QRS was selected from a lead with a prominent QRS complex, and the signal averaged over the order of 30 beats. The RMS value of the averaged QRS complexes was calculated for the individual difference leads as well as for **L**. The average signal was then subtracted from each signal to provide an estimate of the noise. The RMS of the noise was then calculated.

RESULTS

The average voltage in the difference leads was 83 ± 42 μV for the chest region and 44 ± 33 μV for the shoulder region. The RMS noise level in the individual difference leads was 16 ± 11 μV for both regions. The average signal to noise ratio of the surface Laplacian was 3.25 ± 1.26 for the chest recordings and 2.46 ± 1.97 for the shoulder recordings. Three of the 20 shoulder recordings exhibited signal to noise ratios of less than one.

For the chest recordings on the 10 subjects, a comparison of **L** recorded with the two electrode orientations showed that 4 waveforms were similar and 5 waveforms were grossly different. For the shoulder recordings with the two orientations, 4 were similar and 5 were grossly different. There was no consistency among subjects with regard to similarity of chest and shoulder determinations of the surface Laplacian. There was considerable variation in the amplitudes and waveshapes of **L** recorded at the chest and shoulder locations among the 10 subjects.

MODEL STUDIES

To put the experimental studies in perspective, model studies were performed using a realistic cardiac source in a homogeneous torso. Two volume conductors were considered, a sphere and a realistic torso. The cardiac source was a 23 dipole model of cardiac excitation and recovery developed by Miller and Geselowitz for the normal heart [3].

Calculations for the sphere used an analytic expression for the potential [4]. The realistic torso was described by 392 triangles. The region where the surface Laplacian was to be determined was subdivided to give a total of between 1745 and 3511 triangles.

The surface Laplacian was calculated at two sites for both the sphere and realistic torso. These sites corresponded to those used experimentally. In all cases the electrode separation, d, was varied from 1 to 4 cm in steps of 1 cm. The angle of rotation of the electrode array was varied in steps of 9°.

For the sphere the value of **L** remained constant as d varied from 1 to 4 cm. The total change was less than 2%. Furthermore as the angle varied, **L** remained constant. For the realistic torso, on the other hand, the peak value of **L** varied from 238 to 121 μV/cm^2 as spacing increased from 1 to 4 cm in the chest region, and from 8.5 to 4.0 μV/cm^2 in the shoulder region.

In contrast to the sphere, **L** for the realistic torso varied with angle. For the chest site for d = 2 cm, the maximum increased by 4.6% and the minimum increased by 11.5% at 45° while for the shoulder the change was 23.3% and 7.7%. Greater discrepancies were observed at some intermediate rotations.

DISCUSSION

Aside from theoretical concerns, there are two practical issues regarding the utility of using the surface Laplacian. One is the signal to noise ratio. The other is the ability to record it on the curved surface of the torso. The present study investigated these aspects with a modest experimental study together with model studies.

The algorithm for **L** involves small difference signals, and may be expected to exhibit poor signal to noise ratio. The experimental data indicated that there are potentially severe signal to noise problems. A low signal to noise ratio would make inverse calculations difficult, and would hamper interpretation of the signals themselves.

One test of the accuracy of the rectangular electrode array is whether **L** is invariant with rotation. Our results reveal substantial effects of rotation. On a flat surface **L** has a simple expression. The expression on an arbitrary surface is extremely complex, and involves the local curvature, and would be difficult to implement. All investigators have used the flat surface approximation. To test the effect of curvature we used the simple expression and compared results with the array rotated 45°. For the 2 cm spacing used vast differences were recorded, indicating severe limitations in the ability to record **L** accurately. The model studies tended to confirm the experimental results, although the variation found was not as severe. For a spherical surface there was no effect of rotation of the electrode array as predicted theoretically. On the realistic torso, however, variations of greater than 23% were obtained in peaks of the biphasic waveform.

The realistic torso model for d = 2 cm gave peak values of **L** of about 150 μV/cm^2 for the chest and 12 μV/cm^2 for the shoulder. The experimental results exhibited a great variation, with 7 of the 10 subjects having higher amplitudes in the chest recordings.

The surface Laplacian has also been measured using a ring electrode, again based on a planar surface. The ring electrode suffers from the additional problem that good uniform contact must be obtained with the skin along the entire perimeter.

These results raise serious questions about the practically of measuring **L** on the body surface.

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