<full paper>
Ergonomics of Human-System Interaction   Vol.15, No.1
Takeda K., Tomita Y. Application of Discrete Laplace's Equation   October, 2013

Application of Discrete Laplace's Equation to Create Topography Map of Near-infrared Spectroscopy Signal

Kotaro TAKEDA[1], Yutaka TOMITA[2]*

[1]Clinical Research Center, National Hospital Organization Murayama Medical Center
[2]Fujita Memorial Nanakuri Institute, Fujita Health University

*Corresponding Author: Yutaka TOMITA, Ph.D.
 Fujita Memorial Nanakuri Institute, Fujita Health University. 1865 Hisaiisshiki-cho, Tsu-shi, 514-1296, Mie, Japan.
 Tel: +81-59-252-1010, E-mail: tomita@z3.keio.jp

Abstract: Near-infrared spectroscopy (NIRS) enables non-invasive measurement of hemoglobin concentration changes in the cerebral cortex. Creation of a topography map is an important evaluation method used in clinical NIRS studies. In this study, we used Laplace's equation method to create topography maps of NIRS. The method was tested and found to converge very precisely. The method was applied to NIRS signals, and it gave a smooth picture, which did not contradict our physiological knowledge. Finally, a noisy signal was omitted and a topography map was constructed without the information of the corresponding channel, with accurate results.

Keywords: Oxygenated hemoglobin, fNIRS, Optical Topography

1. Introduction

Near-infrared spectroscopy (NIRS) enables non-invasive measurement of concentration changes in oxygenated and deoxygenated hemoglobin (Δ[Oxy-Hb] and Δ[Deoxy-Hb], respectively) in the cerebral cortex[1,2], and has been widely used in experimental studies and in clinical practice[3-5] for over a decade because of its simplicity and clinical safety.

During unilateral hand movement of healthy subject, strong contralateral predominant activation in the primary sensorimotor cortex (SM1) can be seen. On the other hand, ipsilateral or bilateral widespread cerebral activation has been shown when stroke patients move their affected hand[6-8]. Thus, to estimate the activation area of stroke patients by NIRS, multi-channel measurement is necessary to cover the contralateral SM1 and several motor related areas, including the bilateral SM1, premotor cortex, and supplementary motor area. In addition, a topography map made from the multichannel data is useful to assess the cortical activation. However, NIRS systems are often unable to perform accurate measurement because of contamination with noise due to subject's hair between the probe and scalp. Although sometimes the noise contamination is inevitable, general NIRS systems do not provide a topography map without the contaminated channels.

In the present study, we propose a novel method to create a topography map from multichannel NIRS signals. To create the map, the number of channel points is insufficient to draw a smooth map and to determine whether a region of interest is active or not. Therefore, we employed the discrete Laplace's equation method to expand the space and interpolate the area. In addition, when some channel signals were found to be contaminated with noise, we omitted the noisy channels and created a topography map without the channels. By using this proposed method, we could create a clear topography map by omitting noisy signals.

2.   Materials and Methods

1)   Performance of iterative solution of discrete Laplace's equation

A matrix V of 90×130 was defined, and the elements of $(5+20i, 5+20j)$, where $i = 0, 1, \ldots, 4; j = 0, 1, \ldots, 6$, are fixed with "1", i.e.,

$$V(5+20i, 5+20j) \equiv 1, \qquad (1)$$

while the rest of the elements were initially filled with "0". We then solved Laplace's equation in the iteration manner until every element of the matrix converged to $(V^k - V^{k-1})/V^k < 0.0001$, where k denoted the k-th iteration, as previously reported[9]. We used a rectangular grid to sample the values in two-dimensional space. The most convenient choice of rectangular grid is the case of $\Delta x = \Delta y$, which represents the sampling of a square grid. Under these circumstances, the discrete form of Laplace's equation becomes:

$$V(i, j) = [V(i-1, j) + V(i+1, j) + V(i, j-1) + V(i, j+1)] / 4 \qquad (2).$$

This equation simply states that a value at any particular point in a uniformly sampled space must be the average of its nearest neighbors. All iterative procedures were performed in Matlab (MathWorks, USA). The MATLAB code is listed in Appendix.

2)   Collection of NIRS signals

Time series of NIRS, $V(i,j;t)$, were obtained with a NIRS system (SMARTNIRS; Shimadzu, Japan), which gave time series of 54 channel signals from 33 probes (Fig. 1). The inter probe distance was 3.0 cm.

3)   Subject and protocol of task

A healthy subject sat on an office chair and 33 probes were mounted on his head. He was asked to use integrated volitional control electrical stimulation (IVES) device (PAS system GD-601; OG Giken, Okayama, Japan). The IVES is a functional electrical stimulation system that is triggered and controlled by the voluntary electromyogram of an attached muscle (e.g., the extensor digitorum communis) to facilitate muscle contraction[10].

For the first 10 s, he was asked to relax and rest, for the next 10 s electrical stimulation was applied on his right extensor digitorum communis, and for the last 10 s he was again asked to rest. This 30 s series was repeated 3 times.
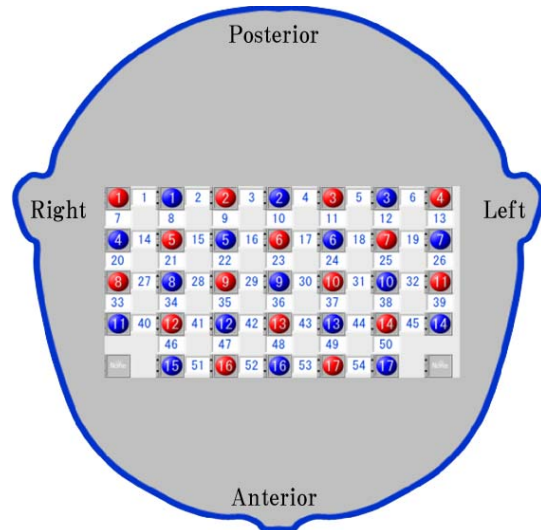

Figure 1 NIRS probe arrangement. Red: Transmitters, Blue: Receivers, White: Measurement channels (Ch1-Ch54). The 23rd channel was placed onto the subject's vertex (Cz of international 10-20 system).

4)   Application for NIRS signals

Three near-infrared laser beams (wavelengths at 780, 805, and 830 nm) were emitted, then reflected beams were sampled at 5 Hz and were used to calculate Δ[Oxy-Hb] and Δ[Deoxy-Hb] for each 54 channels, as shown in Fig. 2. We used Δ[Oxy-Hb] signals to make the topography map because it is the most sensitive indicator of regional cerebral blood flow[2,11] due to neuronal activation. NIRS signals include an unknown optical path length, which is altered by the scalp and tissue structure in the brain[12,13]. Therefore, Δ[Oxy-

Hb] signals were normalized for each channel so that the mean and standard deviation against the 10 s resting period before the first task were 0 and 1, respectively. The signals were synchronously averaged. We analyzed the Δ[Oxy-Hb] signals from the first 10.5 s, i.e., 0.5 s after starting the task.

A matrix of 90×130 was defined and Δ[Oxy-Hb] at 0.5 s after starting the task, $Map(i,j;10.5)$, and were fixed as shown in Table 1. In this study, the data in Ch25 was excluded to make the topography map because the channel could not observe stable reflected lights during calibration before the measurement.

Table 1 Initial values of matrix MAP, with the other elements were set at "0".

| Ch	i	j	Normalized Oxy-Hb	Ch	i	j	Normalized Oxy-Hb
1	5	15	2.12	28	45	35	1.89
2	5	35	0.50	29	45	55	1.27
3	5	55	1.49	30	45	75	1.77
4	5	75	3.36	31	45	95	1.62
5	5	95	3.34	32	45	115	4.50
6	5	115	1.94	33	55	5	2.59
7	15	5	2.39	34	55	25	2.21
8	15	25	1.81	35	55	45	0.78
9	15	45	0.31	36	55	65	−0.96
10	15	65	4.99	37	55	85	2.97
11	15	85	3.77	38	55	105	1.47
12	15	105	3.15	39	55	125	2.38
13	15	125	2.92	40	65	15	3.18
14	25	15	2.76	41	65	35	2.72
15	25	35	1.01	42	65	55	0.62
16	25	55	0.35	43	65	75	2.17
17	25	75	1.47	44	65	95	3.12
18	25	95	3.81	45	65	115	2.29
19	25	115	3.66	46	75	25	3.76
20	35	5	3.29	47	75	45	2.41
21	35	25	3.32	48	75	65	3.20
22	35	45	1.98	49	75	85	1.83
23	35	65	1.20	50	75	105	3.00
24	35	85	2.61	51	85	35	3.93
25	35	105	1.73 → −	52	85	55	2.72
26	35	125	2.28	53	85	75	2.64
27	45	15	0.87	54	85	95	2.70
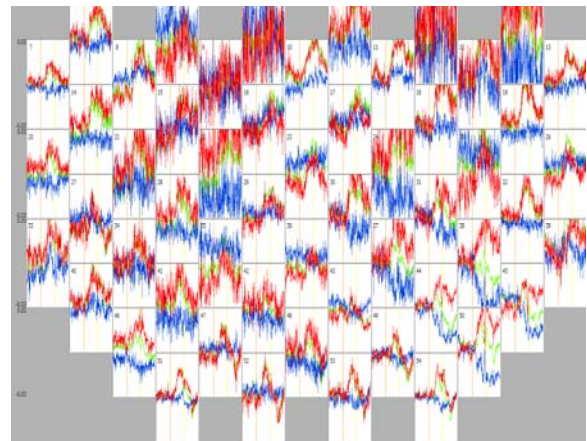
Figure 2 The averaged time series of each channel. Red: Δ[Oxy-Hb], Blue: Δ[Deoxy-Hb], Green: Δ[Oxy-Hb]+Δ[Deoxy-Hb].

3.   Results

1)   Performance of iterative solution of discrete Laplace's equation

The boundary condition given by Eq.(1) is converged as shown in Fig. 3a. The cross section of its bottom is shown in Fig. 3b. These figures demonstrate that the solution converged in (1-0.9993)/1 = 0.0007/1 at most.
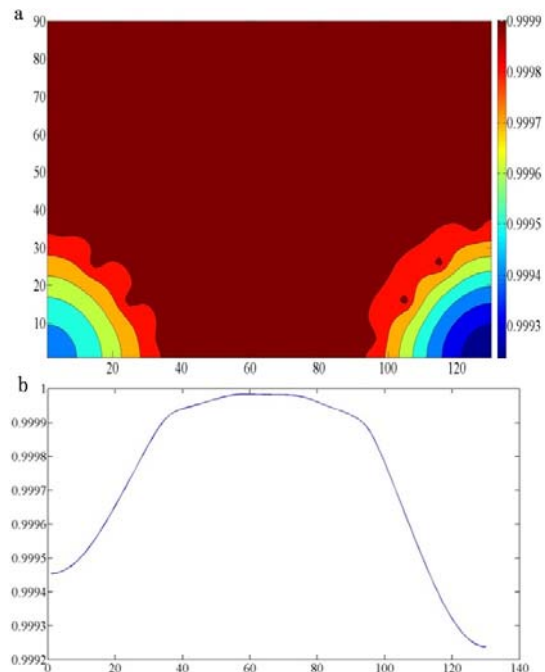

Figure 3 Solution of Laplace's Equation (a) and Cross section at the bottom of the solution (b). Lattice points were set at "1", and the others were set at "0".

<full paper>
Ergonomics of Human-System Interaction   Vol.15, No.1
Takeda K., Tomita Y. Application of Discrete Laplace's Equation   October, 2013

2)   Application for NIRS signals

Starting the calculation with the boundary conditions given in Table 1, with the rest of the elements initially set at "0", the matrix, *Map*, converged as shown in Fig. 4. Using the same boundary conditions in Table 1, except for Ch25 due to noise, the signal of the channel was omitted from the boundary conditions (see Table 1, Ch25, 1.7296 → —), and the matrix, *Map*, converged as shown in Fig. 5.
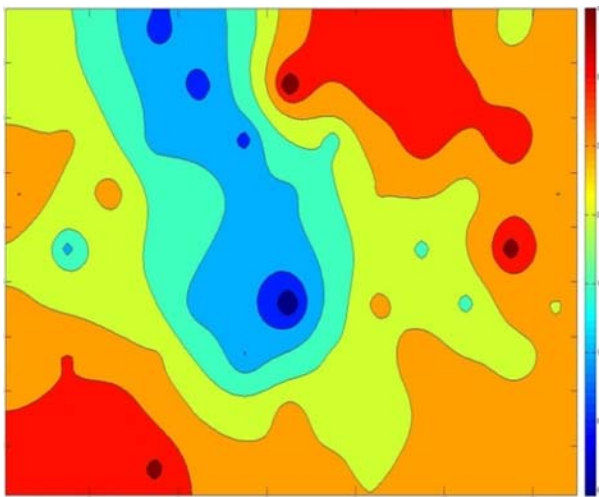

Figure 4 Topography map of NIRS at 0.5 s after starting IVES.
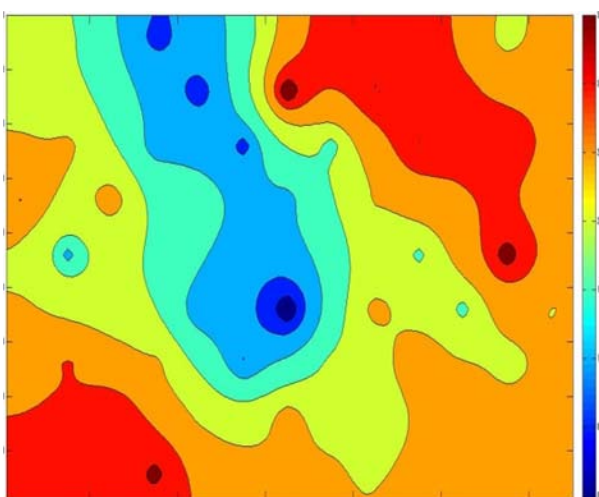

Figure 5 Topography map of NIRS created without noisy 25th channel.

4.   Discussion

1)   Performance of iterative solution of discrete Laplace's equation

Figure 3 demonstrated that the solution converged in 0.0007 at most, because of the sparse arrangement of photo-probes at the lower right and left sides. Thus, the present method was sufficient for creating a NIRS topography map.

2)   Application for NIRS signals

The subject performed an IVIS task, and the left hemisphere was active compared with the right side. These results did not show any contradiction with normal physiology. The topography map by multi-channel NIRS is useful for research and clinical applications. However, general NIRS systems[14,15] do not provide a method for creation of the map without any noisy channels. Consequently, an inexact map is often made. Using our proposed method, we can simply create a reasonable topography map by ignoring noisy channels.

5.   Conclusion

We applied Laplace's equation method to create topography maps of NIRS, and coded the method in Matlab. The method was tested and found to converge very precisely. The method was applied to NIRS signals, and it gave a smooth picture, which did not contradict our physiological knowledge. Finally, a noisy signal was omitted and a topography map was constructed without the information of the corresponding channel.

References

1) Maki A, et al.: Spatial and temporal analysis of human motor activity using noninvasive NIR topography. Med Phys 22(12), 1997-2005, 1995.

2) Hoshi Y, et al.: Interpretation of near-infrared spectroscopy signals: a study with a newly developed perfused rat brain model. J Appl Physiol (1985) 90(5), 1657-62, 2001.

3) Kato H, et al.: Near-infrared spectroscopic topography as a tool to monitor motor reorganization after hemiparetic stroke: a comparison with functional MRI. Stroke 33(8), 2032-6, 2002.

4) Vernieri F, et al.: Hemoglobin oxygen saturation as a marker of cerebral hemodynamics in carotid artery occlusion: an integrated transcranial doppler and near-infrared spectroscopy study. J Neurol 253(11), 1459-65, 2006.

5) Takeda K, et al.: Shift of motor activation areas during recovery from hemiparesis after cerebral infarction: A longitudinal study with near-infrared spectroscopy. Neurosci Res 59, 136-144, 2007.

6) Cramer SC, et al.: A functional MRI study of subjects recovered from hemiparetic stroke. Stroke 28(12), 2518-27, 1997.

7) Marshall RS, et al.: Evolution of cortical activation during recovery from corticospinal tract infarction. Stroke 31(3), 656-61, 2000.

8) Serrien DJ, et al.: Functional significance of the ipsilateral hemisphere during movement of the affected hand after stroke. Exp Neurol 190(2), 425-32, 2004.

9) URL: Retrieved Sep. 26, 2013, available from http://propagation.gatech.edu/ECE3025/tutorials/ComputingLaplace/DiscreteLaplace.htm.

10) Muraoka Y: Development of an EMG recording device from stimulation electrodes for functional electrical stimulation. Front Med Biol Eng 11(4), 323-33, 2002.

11) Strangman G, et al.: A quantitative comparison of simultaneous BOLD fMRI and NIRS recordings during functional brain activation. Neuroimage 17(2), 719-31, 2002.

12) Saager RB, Berger AJ: Direct characterization and removal of interfering absorption trends in two-layer turbid media. J Opt Soc Am A Opt Image Sci Vis 22(9), 1874-82, 2005.

13) Yamada T, et al.: Multidistance probe arrangement to eliminate artifacts in functional near-infrared spectroscopy. J Biomed Opt 14(6), 064034, 2009.

14) Watanabe E, et al.: Non-invasive functional mapping with multi-channel near infra-red spectroscopic topography in humans. Neurosci Lett 205(1), 41-4, 1996.

15) Miyai I, et al.: Longitudinal optical imaging study for locomotor recovery after stroke. Stroke 34(12), 2866-70, 2003.

Appendix: Matlab Code for Solving Discrete Laplace's Equation

```matlab
% NIRS color map with interpolation by solving Laplace equation
%CSV data Read [data, header]=xlsread('file name')
filename = uigetfile('.csv');      [data,header] =xlsread(filname);           x=data(:,2:54*3+1);


% Standard deviation before starting tasks
xsd=std(x(1:123,:)); h=x(126,:)./xsd;       m=90; n=130;           map1=zeros(m,n)+eps; map2=map1;
for k=1:10000
    c=-1;
    for j=15:20:115; c=c+1;map1(5,j)=h(1+c*3); end    %1stRow
    %map1(35,105)=map2(35,105);% Delete when you ignore the channel.
    for j= 5:20:125; c=c+1;map1(15,j)=h(1+c*3); end    %2nd Row
    for j=15:20:115; c=c+1;map1(25,j)=h(1+c*3); end    %3rdRow
    for j= 5:20:125; c=c+1;map1(35,j)=h(1+c*3); end    %4th Row
    for j=15:20:115; c=c+1;map1(45,j)=h(1+c*3); end    %5th Row
    for j=5:20:125; c=c+1;map1(55,j)=h(1+c*3); end    %6th Row
    for j=15:20:115; c=c+1;map1(65,j)=h(1+c*3); end    %7th Row
    for j=25:20:105; c=c+1;map1(75,j)=h(1+c*3);end    %8th Row
    for j=35:20:95; c=c+1;map1(85,j)=h(1+c*3); end    %9th Row
    for j=2:n-1;      map2(1,j)=(map1(1,j-1)+map1(1,j+1)+map1(2,j))/3;
                  map2(m,j)=(map1(m,j-1)+map1(m,j+1)+map1(m-1,j))/3;end
    for i=2:m-1;      map2(i,1)=(map1(i-1,1)+map1(i+1,1)+map1(i,2))/3;
                  map2(i,n)=(map1(i-1,n)+map1(i+1,n)+map1(i,n-1))/3; end
    map2(1,1)=(map1(1,2)+map1(2,1))/2;           map2(1,n)=(map1(1,n-1)+map1(2,n))/2;
    map2(m,1)=(map1(m,2)+map1(m-1,1))/2;       map2(m,n)=(map1(m,n-1)+map1(m-1,n))/2;
    for i=2:m-1; for j=2:n-1;
              map2(i,j)=(map1(i-1,j)+map1(i,j-1)+map1(i,j+1)+map1(i+1,j))/4;
    end; end
    for i=1:m; for j=1:n
              if abs((map1(i,j)-map2(i,j)))/map1(i,j) > 0.0001;              map1=map2; end
    end; end
end
MAP=flipud(map1);
figure;contourf(MAP);colorbar
```