Volumetric imaging of hemodynamic effects in the human brain by three-dimensional diffuse optical tomography

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Abstract: We report on the first three dimensional tomographic localization of hemodynamic effects in the brain with diffuse optical tomography. Using a model-based iterative image reconstruction algorithms we localize spatial changes in oxy and deoxyhemoglobin.
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1. Introduction

In recent years there has been a great interest in using diffuse optical tomography (DOT) for monitoring of brain activities and diseases [1-9]. It is now well established that near-infrared light can be used to probe the brain for changes in blood oxygenation and blood volume as they occur during neural activities or injuries that involve hematoma. In brain functional studies researchers typically present topographic maps that show spatially resolved changes in the absorption coefficient during certain exercise, such as finger flexing or breath holds. These maps project the cortical response together with the superficial vascular changes onto a two-dimensional surface map. To date there have been no reports on volumetric reconstruction that show the 3 dimensional spatial distribution of changes in optical properties in the brain during various stimuli.

In this paper we employ a model-based iterative image reconstruction scheme to obtain 3-dimensional volumetric reconstruction of the human head. Performing measurements of the human forehead we succeed to spatially localize changes in the absorption coefficient in the human brain. The main advantages of using a tomographic imaging system are their ability to localize optical changes in 3D space, and thereby isolate cortical activity from more superficial phenomenon.

2. Methods

2.1. Model-Based Iterative Image Reconstruction

For the 3-dimensional reconstruction of optical properties in the human head we employ in this work a model-based iterative image reconstruction (MOBIIR) scheme [10,11]. MOBIIR scheme consists in general of three major parts: (1) a forward model that predicts the detector readings based on a given spatial distribution of optical properties, (2) an objective function Φ that compares the predicted with measured signals and (3) an updating scheme that uses the gradient of the objective function with respect to the optical properties to provide optical parameters for subsequent forward calculations. As a forward model we use the time-independent diffusion equation, which is implemented within a finite-element scheme. We use robin boundary conditions that allow for a refractive index mismatch between tissue and skin. The objective function is given by the mean-square error between predicted and measured data. For the first iteration a homogeneous medium was assumed. The optical properties are updated by calculating the gradient of the objective function with respect to the spatial distribution of optical properties, and performing a line-minimization along this gradient. This gradient is calculated with the method of adjoint differentiation.[10] Typically 15-30 iterations with different gradients are necessary before the algorithm converges. In order to employ the MOBIIR scheme an accurate knowledge of the surface geometry, and of the exact locations of sources and detectors is necessary. This is achieved by employing the method of photogrametry [12].

2.2. Instrumentation

Measurements on the human forehead were performed with a continuous wave instrument [13]. The beam of a laser diode (wavelength $\lambda = 800$ nm) is coupled into one of 15 source fiber bundles. Fast switching between different sources is possible by means of an optical demultiplexer, which consists of a mirror that is rotated by a microprocessor-controlled brush-less DC servomotor. A microprocessor equipped motion control unit allows up to ~50 start-stop-motions per seconds. Each source fiber bundle (1-mm diameter) forms one branch of a bifurcated fiber bundle and joins the other branch (3-mm diameter), which is used for light detection, in a bulls-eye's geometry on the target surface. Each detector fiber bundle terminates at one silicon photodiode of a multi-channel detection module. This module incorporates analog signal conditioning hardware such as adjustable gain stages to increase the dynamic range of

detection, up to four lock-in amplifiers, and sample-and-hold circuits in order to improve signal quality and for timing purposes. The output voltages of the detector channels are measured by a data acquisition board and stored on a personal computer. The optical power sent to the target is about 10 mW. With this set up three full tomographic data sets (8 sources x 8 detecors = 64 s-d combinations) are acquired per second.

2.3 Experimental Protocol

The experiment was designed to look at functional hemodynamic changes in the forehead of a single human subject induced by a Valsalva maneuver. During the Valsalva maneuver a forced expiration against a closed glottis demonstrates the effects of changes in intrathoracic pressure on blood pressure, and the brain's auto-regulatory response to decreased vascular perfusion pressure in cerebral vessels. For the measurement the subject was placed in the supine position. Three epochs consisting of Valsalva maneuvers with one-minute restperiods interspersed were performed.

3. Results

An example of a measurement and reconstruction is shown in Figs. 1 and 2. Figure 1a shows the location of the 15 sources and detectors on the forehead. Figure 1b displays 14 traces of measured intensity during a valsalva maneuver with the source at position 3. As can be seen in Fig. 1b, during the valsalva maneuver the measured signal changes substantially for all detectors. In general measurement intensities changed with respect to the rest period by up to 50% during the maneuver.
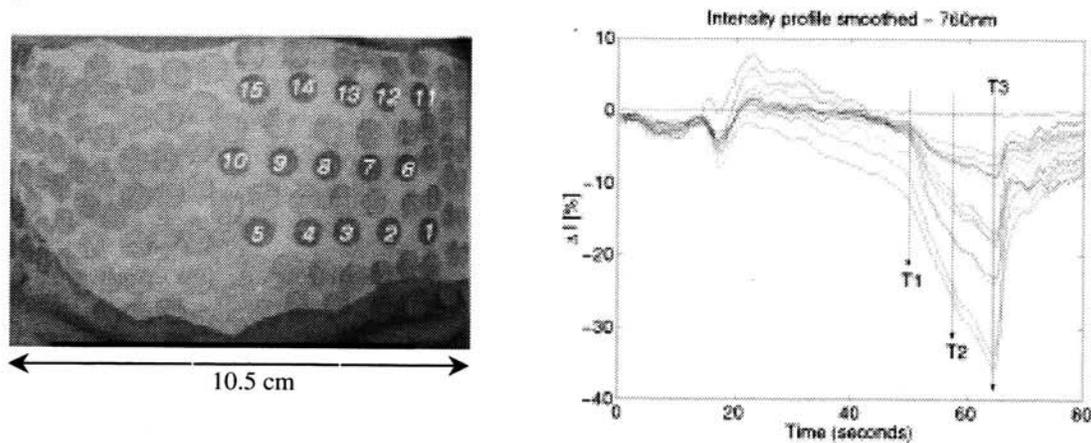

Fig. 1. (a-left) Placement of sources and detectors on forehead. The 15 source/detector position are indicated by the encircled numbers. Other round dots indicate reference points used for the photogrammetric surface determination. The lighter shaded area depicts the outer surface of the finite-element mesh, which was used for the volumetric image reconstruction. (b-right) Changes in intensities as measured for 8 detectors given one source (white dot in Fig. 1a). Similar curves are obtained for all source positions. The data sets indicated by the arrows are input to the model-based image reconstruction code.

For the reconstructions shown in Fig, 2, we used the data sets indicated by the T1 and T3 in Fig. 1. Shown are volumes with various changes in the concentration of oxyhemoglobin in three different views (frontal- upper left corner, side- upper right corner, and arial-lower left corner). These changes occur at a depth of approximately 1-2 cm, and therefore appear to be located in the cerebral cortex and not the overlying tissues.

4. Discussion

By using a MOBIIR scheme, the volumetric reconstruction, is in principle capable of separating blood oxygenation effects from deoxygenation effects. Hence, one can suggest that the changes in oxygenation are associated with factors affecting cerebral blood flow, while the changes in deoxygenation may reflect venous pooling. Our findings seem to indicate that flow changes are the more dominant effect over the forehead during the Valsalva maneuver. Also, one might expect that the resulting cerebral blood flow changes would produce a more spatially uniform hemodynamic change, rather than the localized points of activation as observed initially in Fig. 2. However, these initial punctated changes may be explained by the interaction of light with both the superficial and deep vascular beds. Specifically, a superficial scalp vessel sitting close to a detector on the surface may mask the deeper phenomenon and produce images showing focal points of changing hemodynamics. As one maintains a sustained expiration against a closed glottis the deeper vascular changes contribute a larger portion to the recorded signal and deeper, more spatially uniform, images become visible.

We have presented the first demonstration of a volumetric optical tomographic reconstruction from experimental measurements on the human head. Further studies on the particular source-detector arrangements and its effect on the spatial localization are necessary to fully explore the potential of this technique.
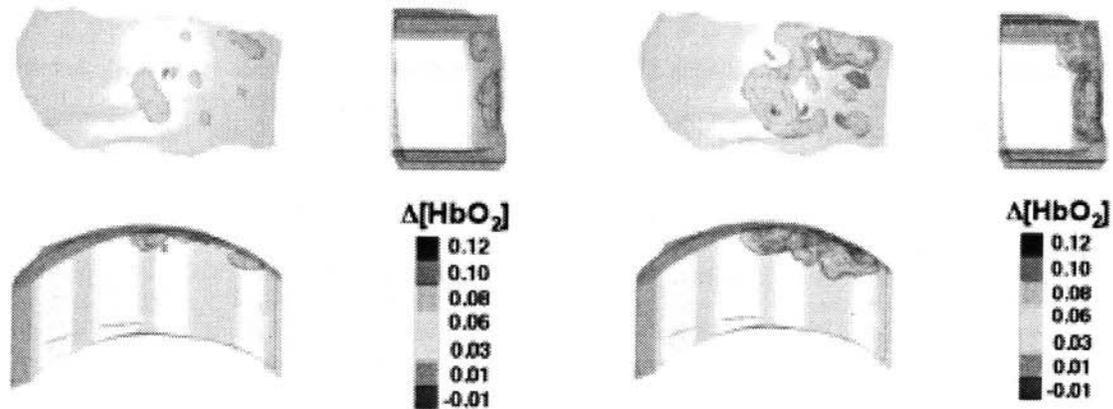

Fig. 2. Volumetric image reconstruction of absorption changes in the human forehead. Both images consist of 3 different views (front-upper right corner, side-upper left corner, and arial-lower left corner). The reconstruction in Fig. 2a (left) is based on data recorded at time point T1 (Fig. 1), and Fig. 2b (right) uses data from time point T3 in (Fig. 1). The changes in oxyhemoglobin are indicated in units of mM.

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