Independent component analysis for intraoperative functional brain mapping using laser Doppler imaging

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Keywords Laser doppler imaging · Neurosurgery · Independent component analysis · Intraoperative brain mapping · Blood perfusion

Purpose

Intraoperative functional brain mapping during neurosurgery is useful prior to surgical removal of lesions close to functionally important regions. Presurgical planning benefits a lot from structural and functional magnetic resonance imaging and its integration with 3-D models in the neuronavigation station. Moreover, direct cortical stimulation during surgery allows testing interference with function in crucial regions, but is a long and tedious procedure. Laser Doppler imaging (LDI) is a promising approach for intraoperative optical imaging of the cortical surface that can provide complementary information to the surgeon in the theatre. LDI allows visualizing blood perfusion in a relatively large field-of-view. Thanks to neurovascular coupling, perfusion serves as a proxy for neuronal activation. Proper stimulation (e.g. motor task) can then be used to delineate the implicated brain regions.

Analysis of LDI perfusion data is challenging due to the many factors contributing to the signal. Previously, this data was analyzed by fitting a general linear model (GLM) and subsequent statistical hypothesis testing. However, the GLM should be specified a priori and many signal components are unpredictable (e.g. acquisition artifacts) or can only be estimated unreliably (e.g. physiological components such as cardiac or respiratory cycles are temporally aliased).

In this work, we propose a combination of modern exploratory techniques with model-based approaches, in particular, independent component analysis (ICA) with GLM analysis. Specifically, the relevance of each independent component with respect to the stimulation paradigm is assessed. This way, we can select components that are relevant and at the same time provide a flexible framework to separate "nuisance" contributions (e.g., physiological components and acquisition artifacts).

Methods

The LDI device is integrated beneath a surgical microscope (Zeiss Pico). The field-of-view is 4x3.5 cm (matrix 140x120 pixels). Illumination at wavelength of 808 nm to image total blood flow (equal absorption of oxy- and deoxy-hemoglobin). Perfusion maps are produced at a frame rate of 1.48 Hz.

ICA is a blind source separation method that identifies spatial components and associated time-courses according to a criterion that favors spatial statistical independence. The number of components was selected after visual inspection of the dimensionality reduction using principal components analysis and fixed here at 25. For each independent component, we fit a GLM that contains the ideal response function (i.e. stimulation function convolved with the canonical hemodynamic response function) and the baseline function (i.e. constant). The absolute value of the t-value for the fitted response is then used to sort the ICA maps. The maps are converted into z-scores using established methodology.

Results

LDI perfusion data was acquired intraoperatively from a male patient (44y) with anaplastic astrocytoma (WHO °III) close to the dominant (left) dorsal inferior frontal gyrus. The patient was fully

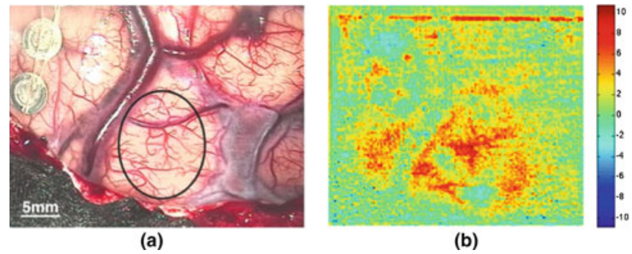

Fig. 1 (**a**) Optical image of the brain region under investigation. The black circle corresponds to the area declared "active" for fingertapping during presurgical fMRI. (**b**) Statistical parametric map for LDI perfusion data after conventional GLM analysis for the fingertapping response. Color bar represents *t*- values. Threshold at 4.56 corresponds to 5% significance level (corrected for multiple comparisons)

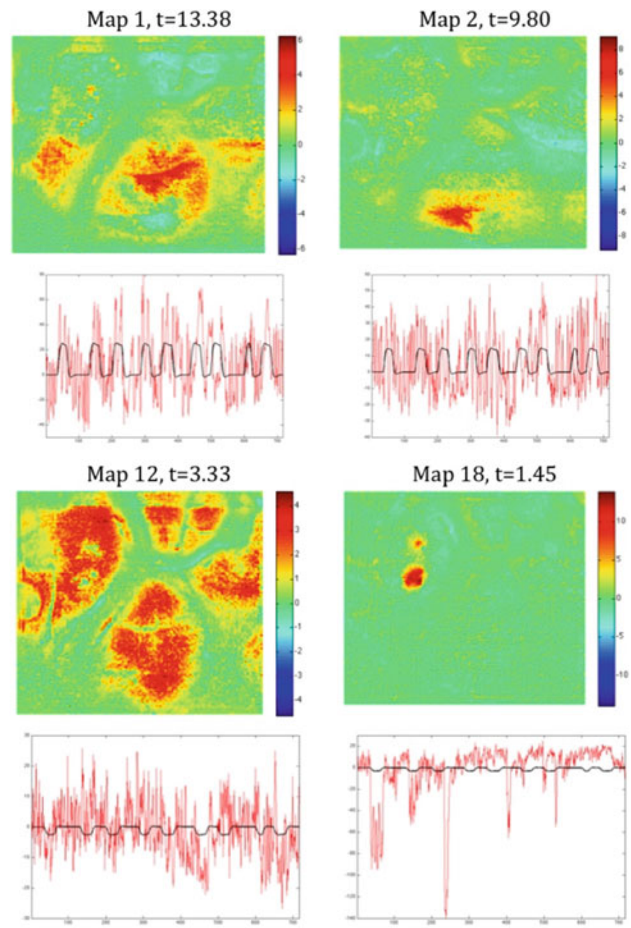

Fig. 2 ICA maps and associated time- course (red) together with the fitted response function (black). Color bar represents (spatial) z-scores of the ICA map. The *t*- value indicates the statistical significance of the temporal fit. Mapx 1 and 2 are clearly stimulation- related components. Map 12 is not related to stimulation but has a very global response; the oscillatory nature of the timecourse suggests a wide pread physiological component. Map 18 is an artifactual component that captures specular reflections from a part of the field-of view

awake during surgery and motor and language function was mapped using standard cortical electrostimulation at 5 mm intervals. During LDI acquisition, a stimulation protocol for fingertapping was performed using a visual cue. Nine fingertapping periods were performed during 8 minutes.

In Fig. 1, we show the conventional optical image of the field-of-view together with the region (black circle) that was located using presurgical fMRI for a similar fingertapping task. The statistical parametric map using GLM analysis is shown on the right side.

In Fig. 2, we depict a selection of ICA maps and time-courses after temporal sorting. Maps 1 and 2 have associated time-courses that are highly correlated to the response function, with very high statistical significance. Interestingly, these maps show a slightly different brain region. Close inspection of the respective time-courses reveals that map 2 is almost exclusively activated for the 7th fingertapping period and this activated area remains inactive for map 1. This suggests that the patient might have performed a slightly different task (e.g. different finger).

The remaining maps are not strongly related to the stimulation paradigm. Map 12 shows the complete exposed cortical surface and the associated time-course is very oscillatory, suggesting a (widespread) physiological component. Many maps capture acquisition artifacts, such as map 18 for some surface reflections. Some other maps also contain stripe artifacts, such as those in the upper part of the map "detected" by standard GLM analysis. The ability of ICA to identify nuisance components is very useful and has been reported before for other modalities such as EEG and fMRI.

Conclusion

The combination of ICA with GLM analysis can be advantageous for analysis of LDI perfusion data. Indeed, many signal components in this modality are (too) unpredictable and can hamper GLM-only analysis. On the other hand, ICA can eliminate nuisance components while at the same time identifying components that are consistent with the stimulation. Moreover, the method is computationally attractive (a couple of seconds for the 8-minutes dataset here) and repeated application of the ICA algorithm rendered almost identical maps.

The use of LDI in the operating theatre may assist the neurosurgeon and considerably shorten the time for mapping the exposed brain. It can also be used with more complex stimulation paradigms without the risk of inducing seizures. There is also a direct correspondence between the current brain position and the view of the surgeon through the surgical microscope ocular.

The observations were carried out with the approval of the ethics committee of the University Clinics of Frankfurt am Main and with the patient's written informed consent.

User interface for decision of intended movement and its application to fracture-reduction assisting robotic system

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Keywords Fracture reduction robot · User interface · Femur shaft fracture

Purpose

Fracture reduction of the lower limb is burden work due to the weight of the limb and the soft tissues around the femur, and requires operator highly qualified skill and experience to figure out three dimensional positions of bone fragments seeing only two dimensional fluoroscopic images. In order to overcome these issues, we have developed a fracture-reduction assisting robotic system for hip fracture and have already reported the navigation based control of the system [1]. Another application of the system is a power assistance mode of an orthopedic surgeon where the robot augmented the surgeons force to generate enough power required for fracture reduction. We installed a force/moment sensor for estimating the operator's intended moving direction; forces are considered translational movements and moments are considered rotational movements. Because forces and moments are always acted on the same time, it is difficult to separate the translation and rotation motions from them. However our medical staffs preferred to separate the translation and rotation movement of bone for more precise reduction. Though menus on a touch panel are prepared for this purpose, it requires one more medical staff because an operator does not want to touch the panel or cannot touch it from concerns of infection.

We are planning to conduct clinical test of our system. So we select a femur shaft fracture as the first clinical application because it has more simple anatomical structure than that of a hip fracture. The purpose of the study is proposal of new interface to decide operator's intention of motion direction based on force/torque sensor data, implementation of the proposed method in the actual fraction-reduction robot, and quantitative evaluation of the reduction accuracy utilizing proposed intention estimation algorithm.

Methods

System configuration

The fracture-reduction assisting robotic system consists of the fracture-reduction robot and the navigation system. Structure of the fracture-reduction robot is provided in Fig. 1(a); a kinematic model and the coordinate of the robot are provided in Fig. 1(b). The fracture-reduction robot has six DOFs (i.e., three DOFs in translation and three DOFs in rotation). The fracture-reduction robot has three interface devices; a touch panel, a foot switch, and a force/moment sensors installed handle. The touch panel provides menus for selecting a control mode of the robot and submenus about each control mode. A surgeon should push a foot switch during operating the fracture-reduction robot with a power assist mode. The handle, whose function is similar to a joystick, is prepared to manipulate the fracture-reduction robot.

Control methods and User interface for decision of intended movement

As the inputted forces and moments by operator, the fracture-reduction robot moves the relevant axes of the robot by centering on the bone coordinate with the proposed control method. The origin of the bone coordinates is on the center of the fracture surface and its primary axis aligns with the longitudinal direction of the bone fragment. Surgeons can track the bone fragment according its longitudinal direction or can rotate the bone fragment

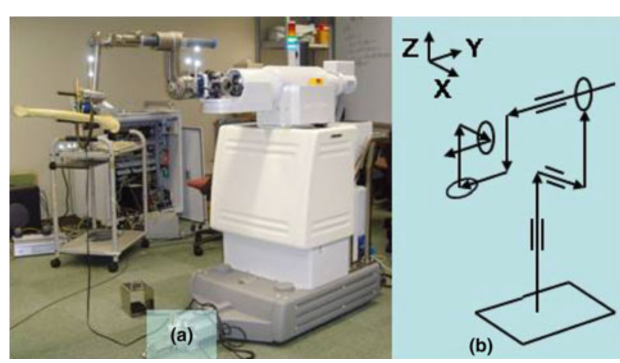

Fig. 1 The fracture reduction robot; (**a**): Structure of the fracture-reduction robot, (**b**): a kinematic model and a coordinate of the robot