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Realignment strategies for awake-monkey fMRI data

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Abstract

Functional magnetic resonance imaging (fMRI) experiments with awake nonhuman primates (NHPs) have recently seen a surge of applications. However, the standard fMRI analysis tools designed for human experiments are not optimal for NHP data collected at high fields. One major difference is the experimental setup. Although real head movement is impossible for NHPs, MRI image series often contain visible motion artifacts. Animal body movement results in image position changes and geometric distortions. Since conventional realignment methods are not appropriate to address such differences, algorithms tailored specifically for animal scanning become essential. We have implemented a series of high-field NHP specific methods in a software toolbox, fMRI Sandbox (http://kyb.tuebingen.mpg.de/~stoewer/), which allows us to use different realignment strategies. Here we demonstrate the effect of different realignment strategies on the analysis of awake-monkey fMRI data acquired at high field (7 T). We show that the advantage of using a nonstandard realignment algorithm depends on the amount of distortion in the dataset. While the benefits for less distorted datasets are minor, the improvement of statistical maps for heavily distorted datasets is significant.

Keywords: Functional magnetic resonance imaging; 7 Tesla; Macaque monkey; High-field fMRI; Primate; Realignment

1. Introduction

For various reasons, the use of a conventional processing pipeline for human functional magnetic resonance imaging (fMRI) data is not appropriate for data from awake nonhuman primates (NHPs) acquired at high magnetic field (7 T) without specific adaptations. One assumption underlying popular realignment algorithms, such as the one used by SPM [1] (Wellcome Department of Imaging Neuroscience, London, UK, http://www.fil.ion.ucl.ac.uk/spm/), is conservation of the subject's head shape across time within a session, with possible shifts and rotations in any direction. In high-field awake-NHP scans, because the subject's head is not free to move, motion in the conventional sense is not an issue. But because of the sensitivity of the high field to jaw and body movements, other more complex issues arise.

With increasing field strength, subject movement has a correspondingly larger impact on image quality. Because they significantly alter the B_0 field at high field strength, subject movements during image acquisition can cause substantial image distortions and signal changes, e.g., Refs. [2–4]. An inevitable source of such distortions is jaw movement, since NHPs participate for juice reward. Swallowing also causes image warping [5], and artifacts can be introduced by body or limb movements. An established procedure to detect and prevent such movements is training the animals to remain still during trials with the help of motion sensors [3], but despite these precautions, motion-related artifacts can remain. In multisegment echo planar imaging (EPI), large body or jaw movements can lead to image degradation in the form of severe ghosting. Shifts of the brain slices in the anterior–posterior (A-P) plane can also accompany a position change of the animal.

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Established rigid-body co-registration algorithms, like the ones employed in standard software, have successfully been used to realign awake-NHP fMRI data. Different methods have been proposed [3], yet no systematic investigation of their effects has been reported. For this study, we tested several different realignment methods and compared their performance to the SPM2 realignment algorithm.

2. Materials and methods

2.1. Animals and implants

Three datasets from two male macaque monkeys (*Macaca mulatta*), M1a,b and M2, body weight 9 and 16 kg, were used for the experiments. All procedures were approved by the local authorities (Regierungspraesidium) and complied with the guidelines of the European Community (EUVD 86/609/EEC) for the care and use of laboratory animals. General surgical procedures and implants are described elsewhere [3,6,7].

2.2. Training and task

The animals were trained to remain still during the experiments through standard operant conditioning and the use of motion sensors to measure jaw and body movements [7]. Trials in which movement was detected by the motion sensors were aborted. The task was to maintain visual fixation before and during the presentation of images (M1a, M2) or movies (M1b). After the image presentation, animals had to stay still for another 10 s before reward delivery (fruit juice). The animals were trained not to move during a trial consisting of four periods: pretrial no-motion, fixation, visual stimulation and rest, for a total time window of 18–20 s (for detailed task information, see Fig. 1 in Ref. [7]).

2.3. Imaging protocol

Experiments were carried out in a vertical 7-T magnet with a bore diameter of 60 cm (Bruker, Ettlingen). A single-shot T2∗-weighted echo planar imaging sequence (GE-EPI) was used for M1, and a two-segment GE-EPI was used for M2. In-plane resolutions were 0.75×0.75 mm (M1a/b) and 1.2×1.6 mm (M2). Field of view was 96×96 mm and 115.2×115.2 mm; repetition time was 1000 ms/segment. We acquired 14 (M1a), 11 (M1b) or 19 (M2) contiguous slices. Slice thickness was 2 mm gapless. Comprehensive localized shimming was done at the beginning of every session. For more information on the gradient system or coils, please see our earlier publications [7,8].

We acquired functional data in runs of 5 min each.

Each session consisted of several short sequences (runs) of 5 min, in each of which 300 (M1a/b) or 150 (M2) functional volumes were acquired containing a variable number of successful trials.

2.4. Data analysis

2.4.1. Trial selection and data concatenation

For the reasons described above, subject movement needs to be addressed explicitly during data analysis. In our representative sample datasets, movements were most common in intertrial intervals and usually occurred after the end of each trial when the animal was rewarded. Movements during trials were generally detected by motion sensors, and such trials were aborted. In some cases, however, slight animal movement was not detected by the sensors and led to image distortion or ghosting even within a completed trial. If the movement was only slight and the distortions were not instantly visible, it led to image shifts in the phase encoding direction. Such minor movements could also result in serious image degradation, making the images unusable for further processing. For all our analyses and processing steps, we used fMRI Sandbox (http://kyb.tuebingen.mpg.de/~stoewer/), unless otherwise stated.

To obtain a clean time course, we first labeled trial periods and removed all scan epochs outside trials. Trial periods were then automatically checked for motion artifacts in fMRI Sandbox using the ratio of the mean intensity of a predefined area within the brain to the area outside of the brain most affected by ghosting artifacts; thresholds could be manually set and the result inspected online. Data were finally inspected by eye. Where artifacts were detected, data for the whole trial were removed. We thus obtained an apparently continuous, yet temporally discontinuous series of volumes that were devoid of visible artifacts.

2.5. Realignment algorithms

2.5.1. Method 1: original data without motion correction

For comparison purposes, we analyzed each original dataset without motion correction.

2.5.2. Method 2: conventional realignment with SPM2

We used the SPM2 [1] (http://www.fil.ion.ucl.ac.uk/spm/) realignment algorithm as a starting point [9], which performs a rigid-body six-parameter (translations and rotations in the x,y,z-direction) co-registration of the volumes within a series to the first image of a scan. This algorithm is theoretically not optimal for awake-monkey datasets since it has more degrees of freedom than needed. Translations usually occur in the phase direction only and are not due to head, but to body, movement. Rotations are not possible because the head is physically restrained. Interpolation was done with a fourth-degree B-spline.

2.5.3. Method 3: modified realignment with SPM2

A standard realignment algorithm does not give priority to shifts in the phase direction over all other spatial transformations. As rotations and shifts in any other direction were physically impossible, we only compensated for image shifts in the phase direction. We used a modified SPM2 routine to realign every volume in a session to its respective first volume, correcting only apparent motion along the A-P