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Research article

Flexible head-casts for high spatial precision MEG

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HIGHLIGHTS

- We propose a method for constructing flexible head-casts to stabilize the head during MEG scanning.
- Co-registration error is minimized by using MRI images to pre-define fiducial coil locations.
- Within- and between-session movement is <0.25 and <1 mm respectively.
- This enables high reproducibility of source level results.

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ABSTRACT

Background: In combination with magnetoencephalographic (MEG) data, accurate knowledge of the brain's structure and location provide a principled way of reconstructing neural activity with high temporal resolution. However, measuring the brain's location is compromised by head movement during scanning, and by fiducial-based co-registration with magnetic resonance imaging (MRI) data. The uncertainty from these two factors introduces errors into the forward model and limit the spatial resolution of the data.
New method: We present a method for stabilizing and reliably repositioning the head during scanning, and for co-registering MRI and MEG data with low error.
Results: Using this new flexible and comfortable subject-specific head-cast prototype, we find within-session movements of <0.25 mm and between-session repositioning errors around 1 mm.
Comparison with existing method(s): This method is an improvement over existing methods for stabilizing the head or correcting for location shifts on- or off-line, which still introduce approximately 5 mm of uncertainty at best (Adjamian et al., 2004; Stolk et al., 2013; Whalen et al., 2008). Further, the head-cast design presented here is more comfortable, safer, and easier to use than the earlier 3D printed prototype, and give slightly lower co-registration errors (Troebinger et al., 2014b).
Conclusions: We provide an empirical example of how these head-casts impact on source level reproducibility. Employment of the individual flexible head-casts for MEG recordings provide a reliable method of safely stabilizing the head during MEG recordings, and for co-registering MRI anatomical images to MEG functional data.

1. Introduction

In theory, the spatial precision attainable with magnetoencephalography (MEG) increases monotonically with increasing signal strength (Gross et al., 2003; Hillebrand and Barnes, 2005, 2003). In practice however, this increase is difficult to achieve. Two of the main limitations are errors in co-registration between func-

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tional MEG data and anatomical magnetic resonance imaging (MRI) data, and head movement during scanning. Both introduce, at best, ~5 mm of uncertainty about the location of the head relative to the sensors (Adjamian et al., 2004; Gross et al., 2013; Ross et al., 2011; Singh et al., 1997; Stolk et al., 2013; Whalen et al., 2008). Critically, both sources of error non-linearly compromise the forward modelling accuracy (Hillebrand and Barnes, 2011, 2003), and reduce the signal-to-noise ratio (SNR) through topographical blurring (Medvedovsky et al., 2007; Uutela et al., 2001).

Although some progress has been made in minimizing co-registration error (Hironaga et al., 2014; Koessler et al., 2011; Nunez and Silberstein, 2000; Whalen et al., 2008), for example by stabilizing the head during recording (Adjamian et al., 2004; Singh et al., 1997), or compensating for movements both during and after recording (Medvedovsky et al., 2015, 2007; Nenonen et al., 2012; Stolk et al., 2013; Uutela et al., 2001), implementation problems have remained. The sources of residual error include misalignment of surfaces, amplification of small placement errors at the front of the head to large errors at the back of the head, and/or reliance on invariance in fiducial placement within and across experimenters and subjects (Adjamian et al., 2004).

Using 3D printing to create solid head-casts which are moulded to the surface of the head internally and to the inside of the MEG scanner externally, we recently showed reduction of co-registration errors to <2 mm (Troebinger et al., 2014a, 2014b). Although these first solid head-casts gave access to much higher quality data by minimizing both co-registration error and head movement, they covered the eyes and their rigidity reduced participant comfort, particularly for long recording sessions. Here, we present a new head-cast prototype made of flexible polyurethane foam which leaves the eyes uncovered, and is easier, safer, and more comfortable to use. The improved user comfort is primarily because of the flexibility which makes it easier and faster to get into and out of the MEG scanner helmet (dewar). Furthermore, the 3D printing is now based on an MRI image (as opposed to an optical scan used in Troebinger et al., 2014a, 2014b) which both maximises the accuracy with which the cast fits the head, and minimizes co-registration error by predefining the MEG fiducial coil locations in MRI space. We describe the construction pipeline, the within- and between-session head movement for subjects wearing these head casts, and assess the estimated co-registration error. We then show how these improvements give rise to high between-session reproducibility at source level.

2. Materials and methods

This section is divided into two parts. First, we describe the methods used for building head-casts. Next, we describe the scanning procedures for evaluating the head-casts with respect to head stabilization, co-registration, and spatial precision.

2.1. Participants

Data were collected from four healthy adult subjects (4 men, mean age 32.3 years old). All subjects were right-handed and had no history of neurological or psychiatric disease. One (fifth) participant was excluded from the analysis because of recording errors. Informed written consent was given by all subjects prior to scanning and the experiments were carried out after obtaining ethical approval from the University College London ethics committee (ref. number 5833/001).

2.2. MRI data acquisition

In order to construct the head-cast, an accurate image of the scalp surface is required. To get this, we first scanned participants in a magnetic resonance imaging (MRI) system (Fig. 1**a**). Images were acquired using a Siemens Tim Trio 3T system (Erlangen, Germany). During the scan, the participant lay in the supine position with their head inside a 12-channel coil. Acquisition time was 3 min 42 s, plus a 45 s localizer sequence. We were very cautious of skin distortions as any such errors could potentially make the head-cast ill-fitting and therefore uncomfortable. For this reason, participants were not given padding or ear phones, as these could displace the skin on the face, head or neck. To minimize audible noise they were instead given ear plugs. The short acquisition time minimizes motion and potential consequential distortions. We used an radiofrequency (RF) and gradient spoiled T_1 weighted 3D fast low angle shot (FLASH) sequence with the following acquisition parameters: image resolution 1 mm^3 (1 mm slice thickness), field-of view set to 256, 256, and 192 mm along the phase (A–P), read (H–F), and partition (R–L; second 3D phase encoding direction) directions respectively. Susceptibility differences existing at air-tissue interfaces can lead to magnetic field inhomogeneity and subsequent distortions or signal loss in the acquired image. Therefore, to preserve brain morphology we used a single shot approach with high readout bandwidth (425 Hz/pixel) and minimum echo time (2.25 ms). Consequently no significant geometric distortions were expected or observed in the images. A short repetition time (7.96 ms) was used to minimise acquisition time while the excitation flip angle was set to 12° to ensure sufficient signal-to-noise ratio for the resulting anatomical image. To accelerate the acquisition, a partial Fourier (factor 6/8) acquisition was used in each phase-encoded direction.

2.3. Head-cast construction

First, we extracted the scalp surfaces from the MRI data using SPM12 (http://www.fil.ion.ucl.ac.uk/spm/) (Fig. 1**a**). This consists of registering the MRI image with a tissue probability map (Ashburner and Friston, 1997) and classifying tissues into different classes (such as grey matter, skull, skin, etc) on a voxel-by-voxel basis. This is done by constructing a generative model which takes into account both the voxel-specific prior probability of belonging to a given tissue class, and its intensity in the MRI image. This model also estimates and corrects for the bias field (Ashburner and Friston, 2005). We used the skin tissue probability map and converted this into a surface using the MATLAB function ‘isosurface’. We then converted this tessellated surface into standard template library (STL) format (Fig. 1**b**) commonly used for 3D printing. To specify the shape of the fiducial coils, we used optical white light scanning to obtain a 3D representation of a single coil. This was digitally drawn in 3D and then checked for its accuracy both against the digital white light scan as well as the physical coil, using digital measuring callipers. Next three copies of this virtual coil were placed, as per convention, at the nasion, left peri-auricular (LPA), and right peri-auricular (RPA) sites. Note that this was not strictly necessary as any set of distant scalp locations would have enabled the co-registration procedure. This approach therefore does not suffer from inaccuracies in determining anatomical landmarks, as is commonly the case when placing fiducial coils on the head during MEG data acquisition. One constraint on the placement of the coils was ensuring that the coil-body and extruding wire were flat against the scalp, in order to remove unnecessary stress or movement of the coil when the head-cast was put on or taken off.

The original design (Troebinger et al., 2014b) was altered so as to now include eye-hole extensions, ear flaps which extend down below the ears, and a top spacing-cylinder to accurately position the positive head model in the dewar-helmet (Fig. 1**c**–**f**). The ear flaps facilitate getting into and out of the scanner more easily and safely (see *Safety Procedures* for more details) and also provide an external reference of when the head-cast is touching the top of the dewar.