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Anatomical correlations of the international 10–20 sensor placement system in infants

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Developmental research, as well as paediatric clinical activity crucially depends on non-invasive and painless brain recording techniques, such as electroencephalography (EEG), and near infrared spectroscopy (NIRS). However, both of these techniques measure cortical activity from the scalp without precise knowledge of the recorded cerebral structures. An accurate and reliable mapping between external anatomical landmarks and internal cerebral structures is therefore fundamental to localise brain sources in a non-invasive way. Here, using MRI, we examined the relations between the 10–20 sensor placement system and cerebral structures in 16 infants (3–17 weeks post-term). We provided an infant template parcelled in 94 regions on which we reported the variability of sensors locations, concurrently with the anatomical variability of six main cortical sulci (superior and inferior frontal sulcus, central sulcus, sylvian fissure, superior temporal sulcus, and intraparietal sulcus) and of the distances between the sensors and important cortical landmarks across these infants. The main difference between infants and adults was observed for the channels O1–O2, T5–T6, which projected over lower structures than in adults. We did not find any asymmetry in the distances between the scalp and the brain envelope. However, because of the Yakovlean torque pushing dorsally and frontally the right sylvian fissure, P3–P4 were not at the same distance from the posterior end of this structure. This study should help to refine hypotheses on functional cognitive development by providing an accurate description of the localization of standardised channels relative to infants' brain structures. Template and atlas are publicly available on our Web site (http://www.unicog.org/pm/pmwiki.php/Site/InfantTemplate).

The recent development of non-invasive brain imaging techniques has boosted research in cognitive development. Electroencephalography (EEG) and near-infra-red spectroscopy (NIRS) are particularly convenient when it comes to neonatal/paediatric brain recordings. Both of these techniques rely on an external placement of the recording sensors; an accurate description of the relations between the external anatomical landmarks and the internal cortical structures is therefore of crucial importance to draw robust interpretations from the recorded activity. It is not only true for NIRS, which records cortical activity in the crescent of light between a laser emitter and photodiode detectors; but also for EEG as responses might be more focal in infants than in adults due to the higher medium conductivity at this age (Grieve et al., 2003, 2004; Odabaee et al., 2013). Thus, an insufficient coverage of the head or a misplacement of the sensors relative to the cerebral structures of interest can lead to erroneous conclusions.

The international 10–20 system for electrode placement was originally developed to place EEG electrodes on the scalp in a reproducible manner from one recording to the next (Jasper, 1958). This standardised electrode positioning system is based on external landmarks, and a regular spacing between electrodes. It assumes a consistent relationship between scalp locations and underlying cerebral structures. The validity of this assumption has been demonstrated in adults (Homan et al., 1987; Jasper, 1958; Okamoto et al., 2004). However, very few studies have been conducted to tackle this issue during brain development, with only one post-mortem study in 6 infants, younger than 4 months of age (Blume et al., 1974), and a skull X-ray study in 28 infants between one week and thirteen months of age (Hellstöm et al., 1963).

This last study, which demonstrated a fixed location of the 10–20 system relative to fontanella and sutures, relied on the hypothesis that brain structures were also aligned to these skull markers. Yet, the inhomogeneous growth of the different cerebral lobes (Gilmore et al., 2007), the increase of the slope of the sylvian fissure during childhood (Sowell et al., 2002) and the operculation of the inferior frontal region observed during the first post-natal year are some examples of developmental changes that may affect the relations between brain structures and the 10–20 standardised scalp locations. Furthermore, the head shape

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may vary more during the first months of life than later on due to birth events and sleeping habits that may flatten one side of the head. Two potential sources of inter-subject variability may thus overlap: the external variability of sensor positioning and the internal structural variability.

In this study, we provided a broad description of the cranio-cerebral relationships of the 10–20 standard positions during the first 4 post-natal months, a time of fast developmental changes (i.e. brain volume doubles between birth and 6 months of age), with two distinct approaches to quantify both external and internal variability. We used MRI data, which give access to both external landmarks and cerebral organisation, in a cohort of 16 healthy infants. We worked on 3-D reconstruction of the infant's heads and brains using specific algorithms developed in the BrainVisa software (Cointepas et al., 2001) allowing realistic computations and visualisation of the relations between external and internal landmarks.

We first virtually placed electrodes over infant heads following the standardised 10–20 placement rules. Second, we choose one infant as representative of the group and projected on her the location of the individual electrodes localization after having normalised each infant anatomical image towards this template. Third, we specifically labelled 94 cortical regions (47 on each hemisphere) in our template infant adapting the MNI-space anatomical parcellation proposed for the adult brain by Tzourio-Mazoyer et al. (2002). We were thus able to analyse the electrode placement variability relative to the underlying cortical regions. Fourth, we examined the brain structural variability across our group and computed the main sulcal patterns distribution, to analyse cortical structures variability with respect to the 10–20 system. Finally, we reported electrode-brain distances since NIRS/EEG measurements are particularly sensitive to the depth of the cortical surface from the head scalp. Our description should provide an accurate view of the variability of standardised electrode locations over the scalp, and of their relationship with underlying cerebral structures in infants. It also provides the community with an anatomically defined infant atlas in order to study and describe cortical activity.

Materials and methods

Subjects

Sixteen healthy full-term infants (mean maturational age, that is, chronological age corrected for the gestational age at birth: 9.0 ± 3.6 weeks, range: 3.4–16.3 weeks; 11 boys, 5 girls) were included in this study after their parents gave written informed consent.

Data acquisition

Infants were naturally asleep during MR imaging (no sedation was used). Particular care was taken to minimise noise exposure, by using customised headphones and by covering the magnet bore with special noise protection foam. The study was approved by the regional ethical committee for biomedical research.

T1 and T2 weighted images covering the whole brain were acquired on a 3 T MRI system (Tim Trio, Siemens Medical Systems, Erlangen, Germany) using a 32-channels head coil. To minimise specific absorption rate (SAR) and noise exposure, we used radio-frequency (RF) impulsions with "no SAR", and the "whisper" gradients mode. The total acquisition time was 5 min 32 s (T1w = 2 min 48 s; T2w = 2 min 44 s). T1w images were obtained with a 3-D fast gradient recovery sequence (MPRage, TE/TR/TI = 4.25/1100/2000 ms, parallel imaging GRAPPA reduction factor 2, partial Fourier sampling factor 6/8). Sagittal slices were acquired with a spatial resolution of 1 mm isotropic (field of view = 192 mm; acquisition matrix = 192 × 192, no interpolation at reconstruction; slice thickness = 1.1 mm; 176 slices). T2w images were obtained with a 2D turbo spin echo sequence (TSE, TE/TR = 149/4500 ms, 4 concatenations, parallel imaging GRAPPA reduction factor 2). Axial slices were acquired with a spatial resolution of 1 mm isotropic (field of view = 192 mm; acquisition matrix = 192 × 192, no interpolation at reconstruction; slice thickness = 1.1 mm; 92 slices).

T1w versus T2w images

In this study, we distinguished the variability for sensor placement over the skull from the variability of inner cerebral structures. At this age, the contrast between white and grey matter is weak in T1w images, and T2w images are preferred to analyse brain structures (Barkovich, 2000). By contrast, T1w images provide better information about the head shape, with a good contrast for the fat of the skin. We thus used T1w images to extract head shape and study sensor placement over the head, and T2w images to examine cortical organisation. T1w images and T2w images were registered to each other in each infant using linear transformation and depending on the analysis, we used one or the other sequence.

Template and atlas definition

Amongst our infants, we chose a 7.1 week-old girl as a template, because her age was close to the population's mean age and her head was regular and symmetrical. We also checked that the head was symmetrically positioned in the head coil to avoid that cerebral spinal fluid (CSF) settles on one side. We choose to adapt the Automated Anatomical Labeling (AAL) atlas (Tzourio-Mazoyer et al., 2002) to the infant's brain. We choose this atlas because, on the one hand, it provides a standardised anatomical labelling that is widely used notably in different softwares (e.g. SPM and Brainstorm), and on the other hand, it relies on identification of primary and secondary sulci, which are already clearly visible in the newborn's brain. Instead of manually drawing sulci landmarks on axial slices as it was done for this template (Tzourio-Mazoyer et al., 2002), we benefited from the 3-D reconstruction of the grey–white matter interface and of the automatic recognition of the sulci through the BrainVisa pipeline (Cointepas et al., 2001) to semi-automatically draw the ROIs on the brain surface.

Specifically, we performed the following steps. The first and most difficult step in infant is to obtain a correct reconstruction of the grey–white matter interface. The inner cortical surface was segmented using a semi-automatic segmentation pipeline dedicated to T2w MRI images of the infant brain (validation of this pipeline can be checked in Leroy et al., 2011b), followed by manual correction, when local inaccuracies were detected. In the fast maturing regions, such as the primary cortices, the T2w signal becomes darker with a blurring of the grey–white matter interface. This leads to segmentation inaccuracies particularly in these regions (Leroy et al., 2011a). The human eye being more accurate to follow the cortical ribbon, authors H.S. and F.L. systematically performed a visual inspection of the automatic segmentation along the central sulcus and the medial occipital regions. The 3-D reconstruction of the inner cortical surface was also checked looking for spiky regions, which are created when the grey–white matter interface is inaccurately drawn. Using Anatomist software (Riviere et al., 2000), the segmented white matter mask was projected over the axial MRI slices and author H.S. manually redrew the white matter mask using a one voxel paintbrush in every axial slice when inaccuracies were detected. Corrections were reviewed with F.L. to obtain the better consensus.

The anatomical parcellation was then performed on this corrected 3-D reconstruction of the inner cortical surface (Fig. 1). Through the BrainVisa pipeline (Cointepas et al., 2001), primary and secondary sulci were automatically extracted and labelled (Fig. 1). This step does not raise specific concern in infants compared to adults. Infants' sulci are generally simpler than adults' due to the fact that the tertiary gyration is just starting at this age. The sulci were visually checked by C.K. and relabelled when necessary, directly on the 3-D ribbon-like representations of the sulcal patterns – using Anatomist (Riviere et al., 2000). Corrections were systematically reviewed with F.L., and in difficult

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