UNC 4D Infant Cortical Surface Atlases, from Neonate to 6 Years of Age

Version 1.0

UNC 4D infant cortical surface atlases from neonate to 6 years of age contain 11 time points, including 1, 3, 6, 9, 12, 18, 24, 36, 48, 60 and 72 months of age, thus densely covering and well characterizing the stages of the dynamic early brain development.

0. What this is

Cortical surface atlases play a fundamental role for spatial normalization, analysis, visualization, and comparison of results across individuals and different studies. For adult MRI studies, many cortical surface atlases have been generated and widely adopted, e.g., FreeSurfer surface atlas, PALS surface atlas, ICBM surface atlas, and HCP-MMP atlas. However, the existing cortical surface atlases created for adults are problematic when applied to infant studies, due to dynamic and nonlinear changes of brain size and also different cortical folding and appearance in the infant brain. To more accurately study the early brain development, the longitudinal 4D infant cortical surface atlases are highly desired. To address this problem, for the first time, we have constructed the UNC 4D infant cortical surface atlases from neonate to 6 years of age at **11** densely sampled time points, i.e., 1, 3, 6, 9, 12, 18, 24, 36, 48, 60, and 72 months of age, based on **339** serial MRI scans from **50** healthy infants, with each being scanned longitudinally from birth. Meanwhile, we have also mapped both the FreeSurfer parcellation (Desikan et al., 2006) and the HCP multi-modal parcellation (MMP) (Glasser et al., 2016) onto our 4D infant cortical surface atlases. Of note, these 4D cortical surface atlases have vertex-to-vertex cortical correspondences across all ages, and thus can be easily used for both cross-sectional and longitudinal analyses. These 4D infant cortical surface atlases with very dense time points will greatly facilitate cortical surface-based mapping of the dynamic and critical early brain development in many pediatric studies, e.g., the Baby Connectome Project (BCP)[1].

1. Where to download

The package can be freely downloaded from:

https://www.nitrc.org/projects/infantsurfatlas/

[1] http://iseg2017.web.unc.edu/baby-connectome-project/

It is availably free to the public for the academic research purpose. Note the ownership, copyright, and all rights are retained by UNC-Chapel Hill.

2. What it includes

Our 4D infant cortical surface atlases are distributed in three popular file formats: (1) VTK (*.vtk) format, which can be visualized and processed by any VTK supported toolkit such as ParaView; b) FreeSurfer format, which can be used by the FreeSurfer Package; c) HCP (*.gii) format, which is in accordance with the workbench toolkit developed under the HCP project.

For each of the 11 time points, we provide:

a) The corresponding spherical representation of each hemisphere of the population-average cortical structures (in a densely sampled sphere with 163,842 vertices). The left hemisphere (lh) and right hemisphere (rh) are represented in two different files.

b) The white surface (inner surface), pial surface (outer surface), and center surface (middle surface). These three surfaces are isomorphic to the spherical representation (spherical surface), with vertex-to-vertex cortical correspondences.

c) The sulcal depth, average convexity, mean curvature, and inflated mean curvature of each white/inner surface. These metrics are generally useful for cortical surface registration.

d) The MMP parcellation (Glasser et al., 2016) (with 180 ROIs in each hemisphere) and the FreeSurfer parcellation (Desikan et al., 2006) (with 35 ROIs in each hemisphere).

Fig. 1 shows the constructed 4D infant cortical surface atlases for the left hemisphere at each time point. Columns (a) – (b) illustrate the cortical properties on the standard sphere; Columns (c) – (d) illustrate the corresponding cortical properties on the age-specific population-average inner cortical surface; Columns (e) and (f) illustrate the FreeSurfer parcellation and the MMP parcellation at each time point.

3. File illustration

There are 3 folders, each with one format of the 4D infant cortical surface atlases.

a) For VTK format, we appended all morphological features and the parcellation labels into the surface files. Totally, for each time point, there are 8 files. The typical file name is: [***Month***]/[***Hemi***].[***Surface***].vtk. The illustration of the name field strings is listed in Table 1.

b) For FreeSurfer format, the surfaces, morphological features, and parcellations are provided in separate files. For each time point, there are 22 files. We have followed the FreeSurfer naming strategy to name our infant surface atlases. The typical surface file name is: [***Month***]/[***Hemi***].[***Surface***]; the typical morphological feature filename is:

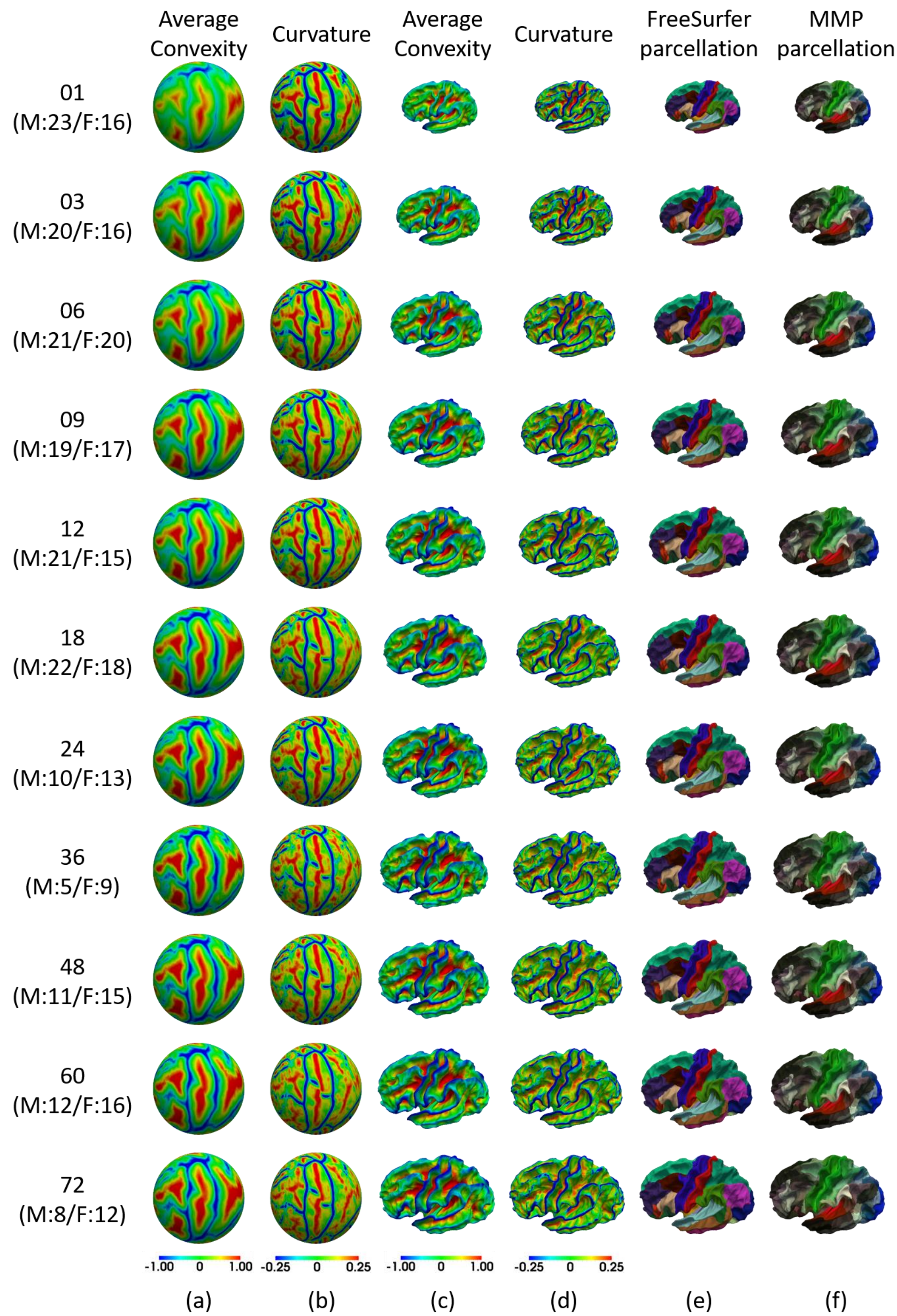

Fig. 1. UNC 4D infant cortical surface atlases and parcellations at 11 time points of age. The subject number with gender information at each time point (with M indicating male, and F indicating female) is provided on the left.

[***Month***]/[***Hemi***].[***Feature***]; and the typical parcellation filename is: [***Month***]/[***Hemi***].*Annot-*[***Parcellation***]. All related name field strings are also listed in Table 1.

c) For HCP format, the surfaces, morphological features, and parcellations are also provided in separate files. For each time point, there are 20 files. We have followed the general HCP naming strategy to name our atlases. The typical surface file name is: [***Month***]/[***Hemi***].[***Surface***].164k.surf.gii; the typical morphological feature filename is: [***Month***]/[***Hemi***].[***Feature***].164k.shape.gii; while, the typical parcellation filename is: [***Month***]/[***Hemi***].[***Parcellation***].164k.label.gii.

Table 1. The name field value for each data format.

Name field	**VTK**	**FreeSurfer**	**HCP**
Month	{01, 03, 06, 09, 12, 18, 24, 36, 48, 60, 72}		
Hemi	{lh,rh}	{lh,rh}	{L,R}
Surface	{InnerSurf, MiddleSurf, OuterSurf, SphereSurf}	{white, center, pial, sphere}	{white, midthickness, pial, sphere}
Feature	Appended into surface {curvature, SulcDepth, Inflated.H, Convexity}	{curv, depth, inflated.H, sulc}	{Curvature, SulcDepth, InflatedCurvature, AverageConvexity}
Parcellation	Appended into surface {par_FS, par_MMP}	{FreeSurfer, MMP}	{ParcellationFreeSurfer, ParcellationMMP}

4. How it was constructed

Totally 339 serial MRI scans from 50 healthy infants, each scheduled to be longitudinally scanned at 1, 3, 6, 9, 12, 18, 24, 36, 48, 60, and 72 months of age, were used to construct UNC 4D infant cortical surface atlases. The subject number with gender information at each time point is provided in **Fig. 1**. All infant MR images were processed by the **UNC Infant Pipeline** for cortical surface-based analysis (Li et al., 2015). Briefly, it included skull stripping, cerebellum removal, intensity inhomogeneity correction, tissue segmentation, separation of left/right hemispheres, topology correction, inner, middle and outer surface reconstruction, spherical mapping, and computation of cortical properties (e.g., sulcal depth, average convexity, cortical thickness, and curvature) (Li et al., 2014a; Li et al., 2014b; Li et al., 2014c; Wang et al., 2015; Wang et al., 2014).

To build longitudinally-consistent surface atlases, both intra-subject and inter-subject surface registrations were performed (Li et al., 2015). Specifically, to establish longitudinal cortical correspondences for each subject, first, the spherical surfaces of all time points for the same subject were registered together using an unbiased group-wise registration method (Yeo et al., 2010). Then, for each subject, a within-subject mean spherical surface was constructed by averaging corresponding cortical properties across all time points. Next, to establish inter-subject cortical correspondences, an unbiased group-wise registration was further performed to align the within-subject mean spherical surfaces of all different subjects. After that, for each age, an age-specific surface atlas (consisting of the mean and variance of cortical properties across all infants at this age) was constructed on the spherical surface, based on the inter-subject cortical correspondences defined above. Finally, a population-specific spherical surface atlas was also obtained by computing the mean and variance of cortical properties across all within-subject mean surfaces.

To equip our infant atlases with parcellations, the population-specific spherical surface atlas was aligned onto the FreeSurfer atlas. Then, for coarse parcellation, the FreeSurfer parcellation with 35 regions in each hemisphere (Desikan et al., 2006) was first propagated to our infant population-specific atlas and then further to our 4D infant cortical surface atlases at all time points. For fine-grained parcellation, the HCP multi-modal parcellation (MMP) with 180 detailed regions in each hemisphere (Glasser et al., 2016) was first mapped to the FreeSurfer atlas using the HCP workbench, and then propagated to our 4D infant cortical surface atlases.

5. How to use

Our 4D infant cortical surface atlases can be used to register an individual's cortical surface into a common space and also propagate the parcellations onto the individual's cortical surface. Here, we provide registration examples for using FreeSurfer[2] (Fischl, 2012) and Spherical Demons[3] (Yeo et al., 2010). After successful install and configuration, the pairwise alignment could be done through the following command lines.

For FreeSurfer, one can use the command:

```
mris_register -1 individual_subject/lh.sphere 4D_altas/lh.sphere individual_subject /lh.sphere.FS.reg
```

For Spherical Demons, one can use the Matlab code:

```
mris_SD_pairwise_register(individual_subject/lh.sphere, 4D_altas/lh.sphere, individual_subject /lh.sphere.SD.reg)
```

When using our 4D infant cortical surface atlases, please cite our following papers:

Li, G., Wang, L., Shi, F., Gilmore, J.H., Lin, W., Shen, D., 2015. ***Construction of 4D high-definition cortical surface atlases of infants: Methods and applications***. Medical image analysis 25, 22-36.

Wu, Z., Li, G., Meng, Y., Wang, L., Lin, W., Shen, D., 2017. ***4D Infant Cortical surface atlas construction using spherical patch-based sparse representation***. MICCAI.

[2] https://surfer.nmr.mgh.harvard.edu
[3] https://sites.google.com/site/yeoyeo02/software/sphericaldemonsrelease

6. Contact

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Li, G., Wang, L., Shi, F., Lyall, A.E., Lin, W., Gilmore, J.H., Shen, D., 2014c. Mapping longitudinal development of local cortical gyrification in infants from birth to 2 years of age. Journal of Neuroscience 34, 4228-4238.

Wang, L., Gao, Y., Shi, F., Li, G., Gilmore, J.H., Lin, W., Shen, D., 2015. LINKS: Learning-based multi-source IntegratioN frameworK for Segmentation of infant brain images. Neuroimage 108, 160-172.

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Yeo, B.T., Sabuncu, M.R., Vercauteren, T., Ayache, N., Fischl, B., Golland, P., 2010. Spherical demons: fast diffeomorphic landmark-free surface registration. IEEE transactions on medical imaging 29, 650-668.