Improved cortical surface reconstruction using sub-millimeter resolution MPRAGE by image denoising

Qiyuan Tian[1, 2*], Natalia Zaretskaya[1, 2, 3, 4], Qiuyun Fan[1, 2], Chanon Ngamsombat[1, 5], Berkin Bilgic[1, 2, 6], Jonathan R. Polimeni[1, 2, 6], Susie Y. Huang[1, 2, 6]

[1]Athinoula A. Martinos Center for Biomedical Imaging, Department of Radiology, Massachusetts General Hospital, Charlestown, MA, United States;

[2]Harvard Medical School, Boston, MA, United States;

[3]Institute of Psychology, University of Graz, Graz, Austria;

[4]BioTechMed-Graz, Austria;

[5]Department of Radiology, Faculty of Medicine, Siriraj Hospital, Mahidol University, Thailand;

[6]Harvard-MIT Division of Health Sciences and Technology, Massachusetts Institute of Technology, Cambridge, MA, United States;

[*]Correspondence to: Qiyuan Tian, Ph.D., Athinoula A. Martinos Center for Biomedical Imaging, 149 13th Street, Charlestown, MA, 02129, United States. E-mail: qtian@mgh.harvard.edu.

Supplementary Information

Methods for 1-mm Isotropic Resolution Data

Data acquisition

For two subjects, T_1-weighted images at 1-mm isotropic resolution were also acquired using the MEMPRAGE sequence for comparing to surface reconstruction results from 0.6-mm isotropic resolution data. The acquisition parameter values were: TR = 2,530 ms, TE = 1.64/3.50/5.36/7.22 ms, TI = 1,200 ms, FA = 7°, 176 sagittal slices, slice thickness = 1 mm, FOV = 256 mm × 256 mm, matrix size = 256 × 256, resolution = 1 mm isotropic, echo spacing = 10.3 ms, bandwidth = 651 Hz/pixel, GRAPPA factor = 3, acquisition time = 4.5 minutes.

Image processing

Spatially varying intensity bias was removed using the unified segmentation routine[1] implementation of the SPM software. For each subject, the 1-mm isotropic resolution image volume was nonlinearly co-registered to the 6-repetition averaged image volume at 0.6-mm isotropic resolution using NiftyReg's "*reg_aladin*" function (default parameters, spline interpolation), which was initialized with an affine transformation derived from NiftyReg's "*reg_f3d*" function (default parameters). The non-linear co-registration slightly adjusted the image alignment locally to account for the subtle non-linear shifts of tissue in the images.

Surface reconstruction

Cortical surface reconstruction at 1-mm isotropic resolution was performed using the standard FreeSurfer (version v6.0) reconstruction pipeline (*"recon-all"* function with default parameters).

Surface accuracy comparison

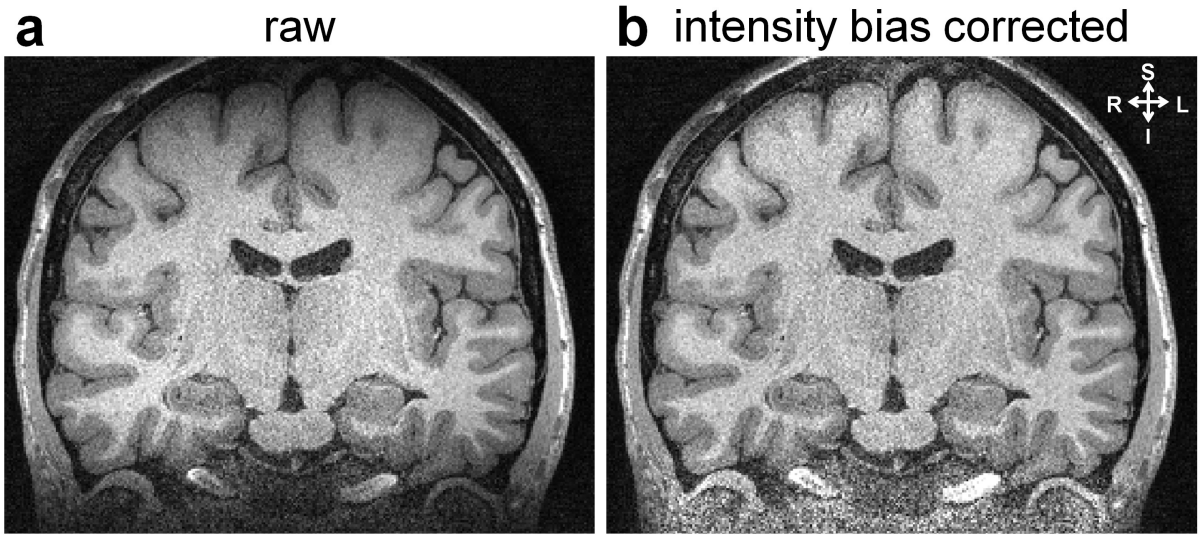
For comparing gray–white and gray–CSF surfaces reconstructed from 1-mm and 0.6-mm isotropic resolution data, the triangular surface meshes generated from 1-mm isotropic resolution data were

resampled onto the corresponding triangular surface meshes generated from the 6-repetition averaged 0.6-mm isotropic resolution data to establish vertex correspondence following the previous study[2]. The vertex-wise displacement of the gray–white and gray–CSF surfaces and the difference of the cortical thickness estimates were then calculated. The FreeSurfer longitudinal pipeline cannot be used for this comparison because the number of vertices of triangular surface meshes generated from 1-mm and 0.6-mm isotropic resolution data is substantially different (~0.5 million vs. ~1 million).

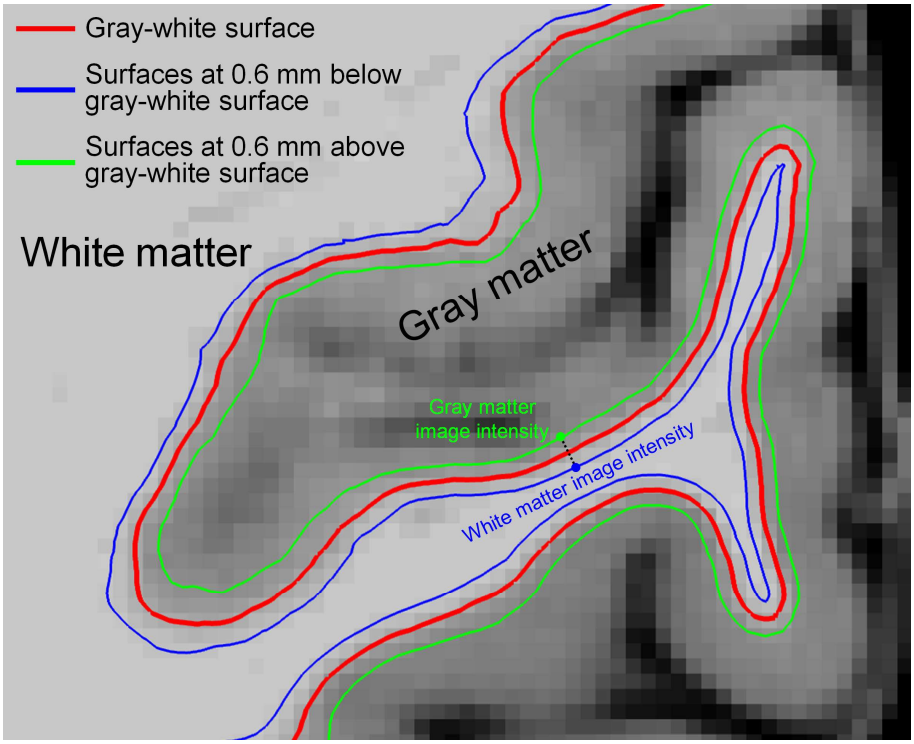
References

1. Ashburner J, Friston KJ. Unified segmentation. *NeuroImage.* 2005;26(3):839-851.
2. Zaretskaya N, Fischl B, Reuter M, Renvall V, Polimeni JR. Advantages of cortical surface reconstruction using submillimeter 7 T MEMPRAGE. *NeuroImage.* 2018;165:11-26.

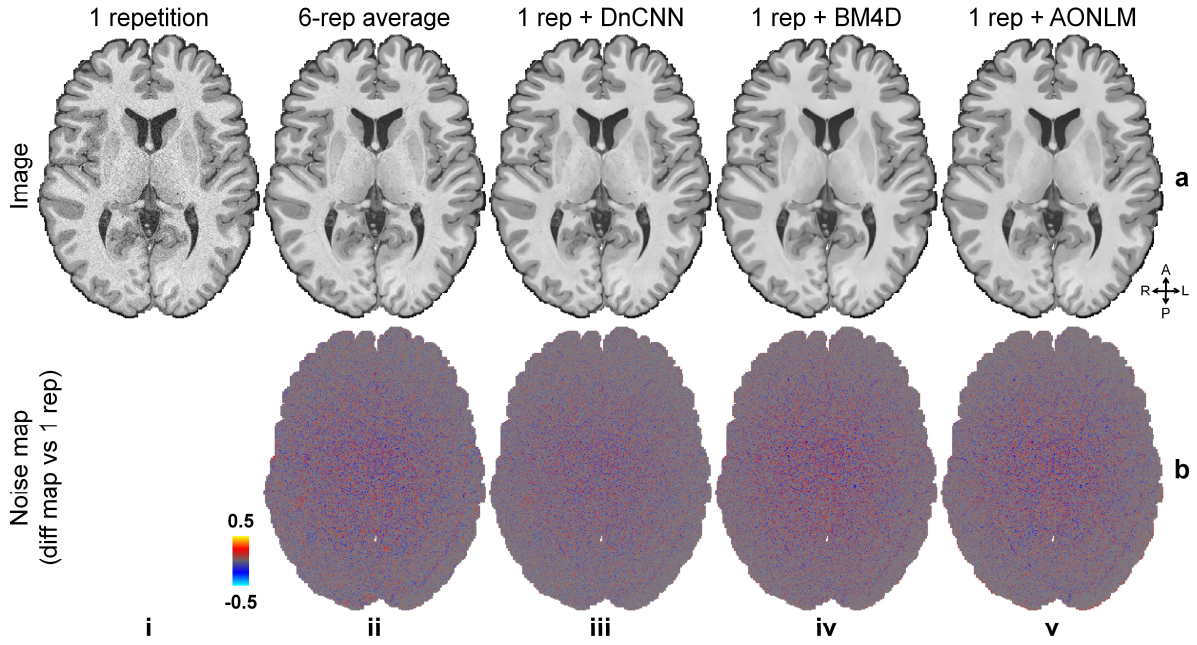
Supplementary Figures and Tables



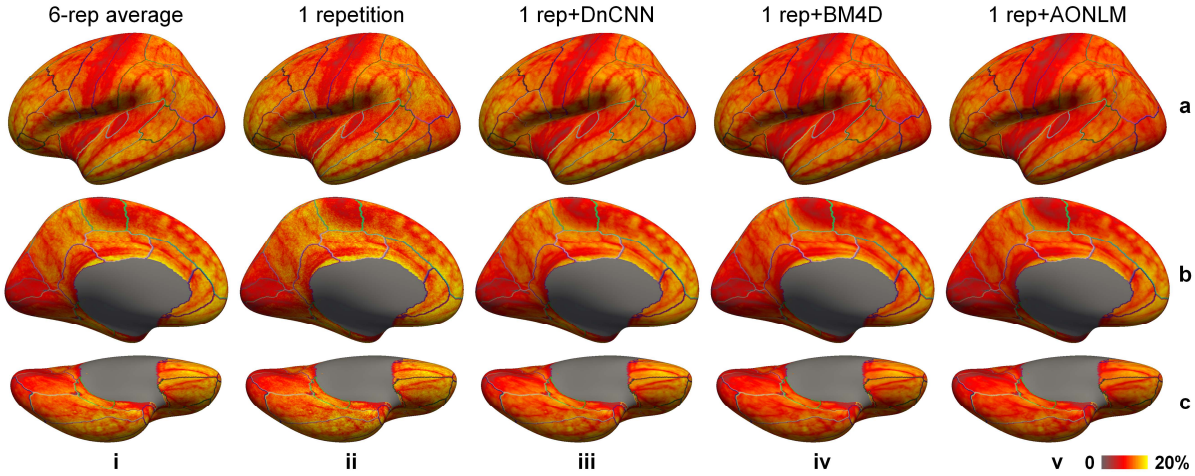
Supplementary Figure 1. Intensity bias correction. A representative coronal image slice from the raw data acquired using a slab-selective oblique-axial acquisition (a) and the same image slice corrected for the spatially varying intensity bias induced by the B_1 field inhomogeneity (b).



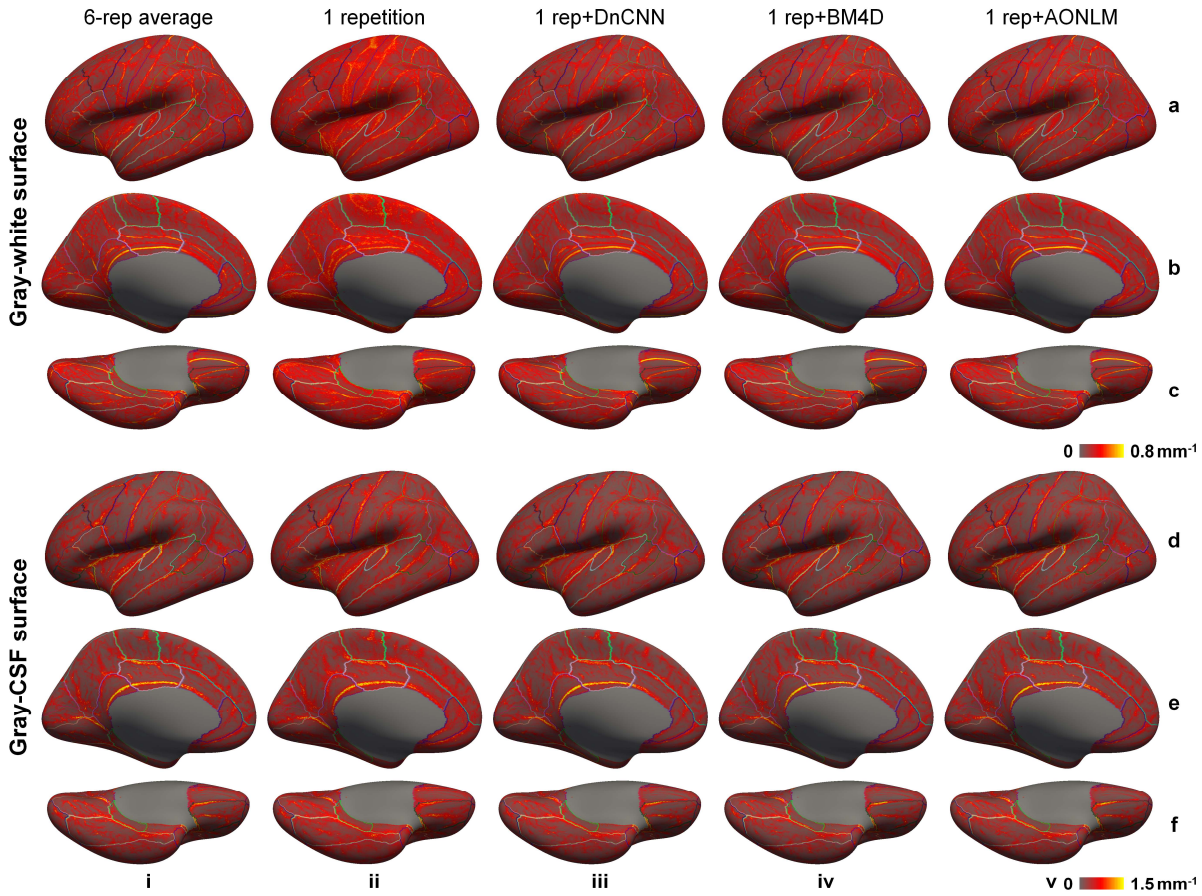
Supplementary Figure 2. Sampling surfaces. Cross-sections of the gray–white surface (red) and the surfaces at 0.6 mm below (blue) and above (green) the gray–white surface for sampling the white matter and gray matter image intensities (blue and green dots) to calculate the gray–white contrast. The surfaces are from the 6-repetition averaged data of a representative subject.



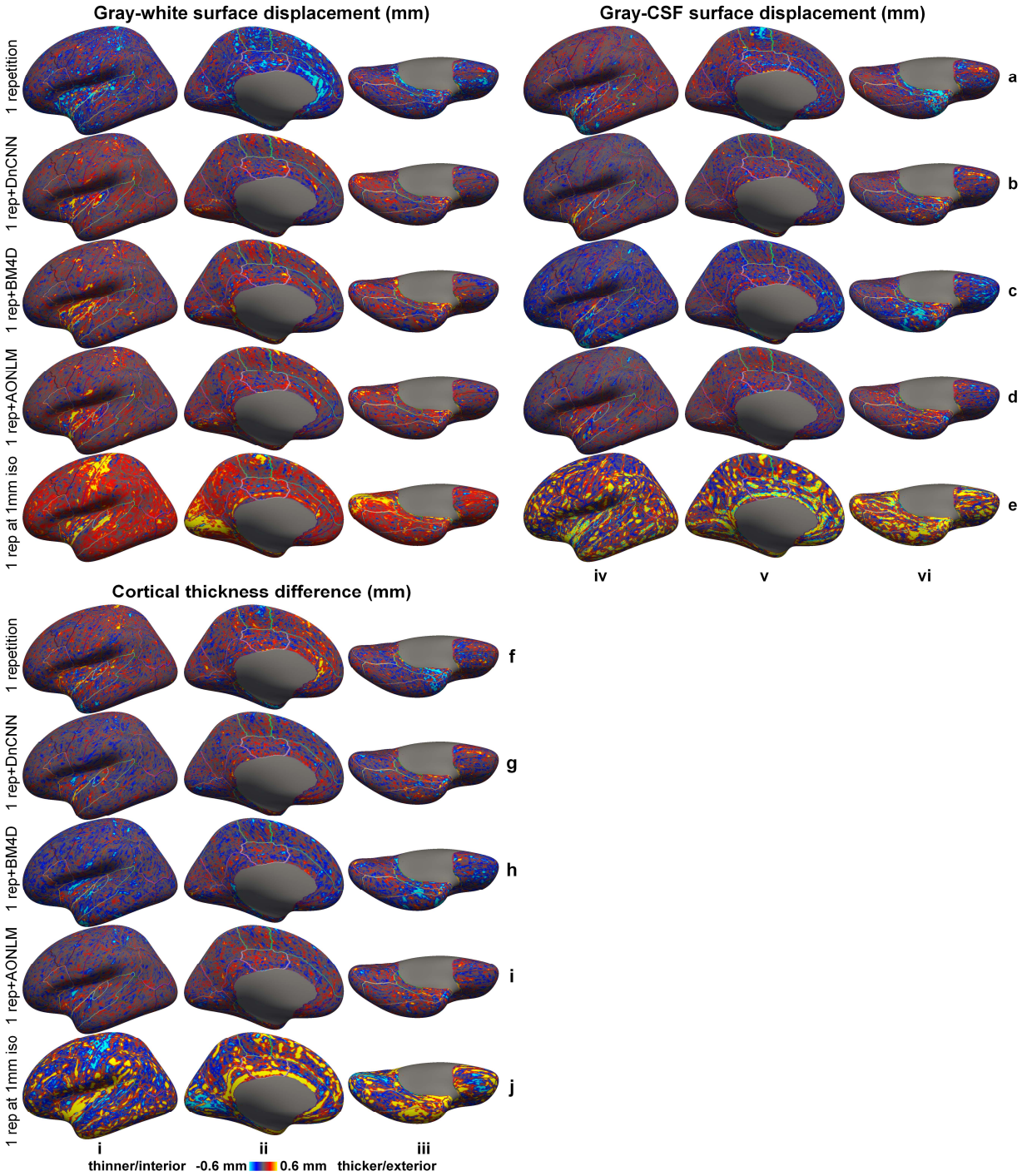
Supplementary Figure 3. Noise estimation. A representative axial image slice from the single-repetition data (a, i), the 6-repetition averaged data (a, ii), and the single-repetition data denoised by DnCNN (a, iii), BM4D (a, iv) and AONLM (a, v), and their residuals (i.e., estimated noise) compared to the image from the single-repetition data (rows a, i).



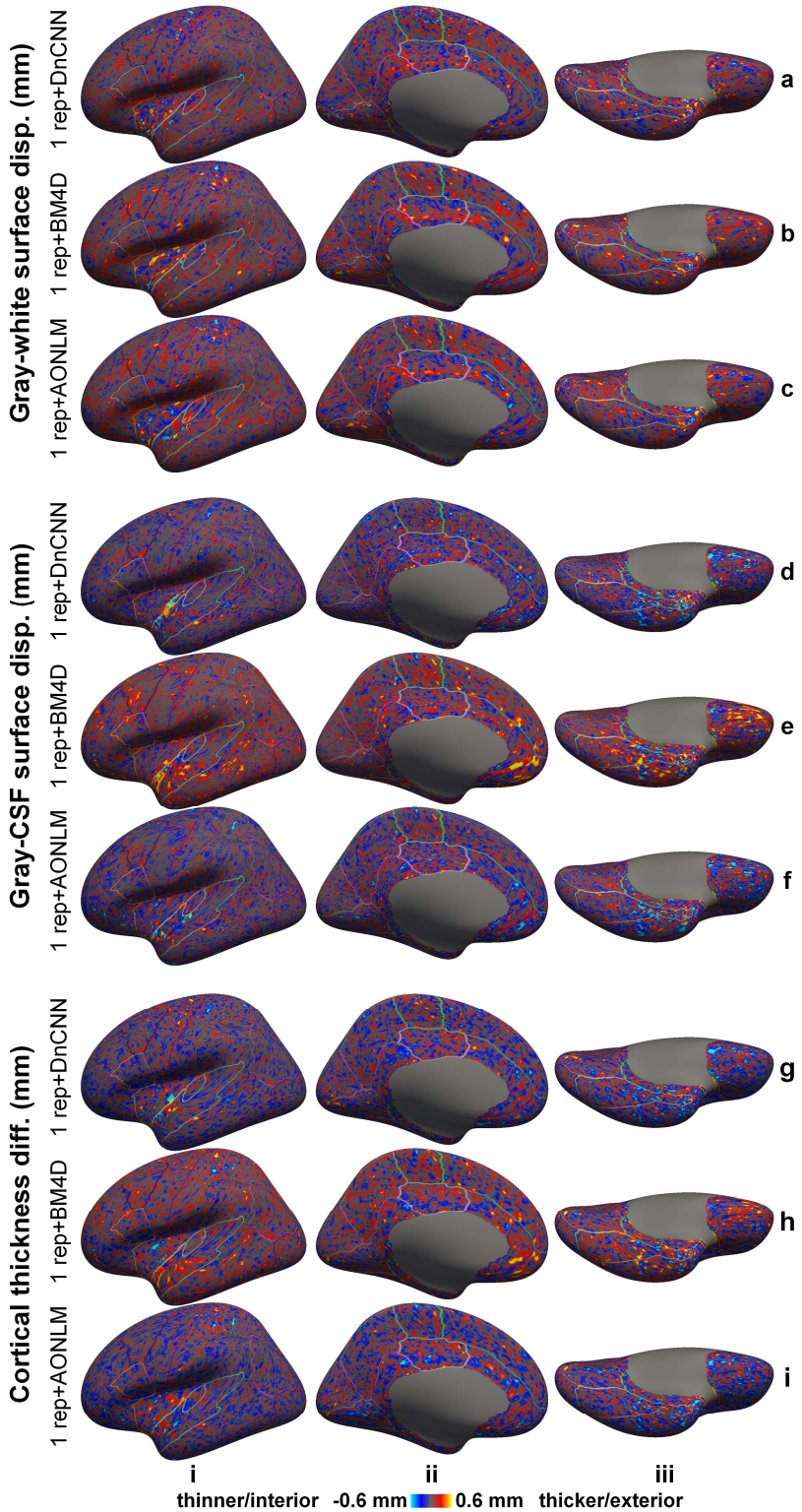
Supplementary Figure 4. Averaged gray–white contrast. Left-hemispheric vertex-wise contrast between the gray matter and white matter image intensity (expressed as [*white* − *gray*]/[*white* + *gray*]·100%) from the 6-repetition averaged data (column i), single-repetition data (column ii), single-repetition data denoised by DnCNN (column iii), BM4D (column iv) and AONLM (column v) averaged across 30 image volumes from the 5 evaluation subjects, displayed on inflated surface representations. Different cortical regions from the FreeSurfer cortical parcellation (i.e., *aparc.annot*) are depicted as colored outlines.



Supplementary Figure 5. Averaged cortical surface smoothness. Left-hemispheric vertex-wise mean curvature of the reconstructed gray–white surfaces (a–c) and gray–CSF surfaces (d–f) from the 6-repetition averaged data (column i), single-repetition data (column ii), single-repetition data denoised by DnCNN (column iii), BM4D (column iv) and AONLM (column v) averaged across 30 image volumes from the 5 evaluation subjects, displayed on inflated surface representations. Different cortical regions from the FreeSurfer cortical parcellation (i.e., *aparc.annot*) are depicted as colored outlines.



Supplementary Figure 6. Positioning and thickness accuracy. Left-hemispheric vertex-wise displacement/difference of the gray–white surfaces (rows a–e, column i–iii) and gray–CSF surfaces (rows a–e, column iv–vi) and cortical thickness estimates (rows f–j, column i–iii) from the single-repetition data (rows a, f) and the single-repetition data denoised by DnCNN (rows b, g), BM4D (rows c, h) and AONLM (rows d, i) at 0.6-mm isotropic resolution, and the single-repetition data at 1-mm isotropic resolution (rows e, j) compared to the surfaces estimated from the 6-repetition averaged data of a representative subject, displayed on inflated surface representations. Different cortical regions from the FreeSurfer cortical parcellation (i.e., *aparc.annot*) are depicted as colored outlines.



Supplementary Figure 7. Positioning and thickness precision. Left-hemispheric vertex-wise displacement/difference of the gray–white surfaces (rows a–c) and gray–CSF surfaces (rows d–f) and cortical thickness estimates (rows g–i) from two consecutively acquired single-repetition data denoised by DnCNN (rows a, d, g), BM4D (rows b, e, h) and AONLM (rows c, f, i) of a representative subject, displayed on inflated surface representations. Different cortical regions from the FreeSurfer cortical parcellation (i.e., *aparc.annot*) are depicted as colored outlines.

Gray-white surface displacement (mm) compared to ground truth from 6-repetition averaged data									
#	Cortices	1 repetition	2 repetitions	3 repetitions	4 repetitions	5 repetitions	1 rep + DnCNN	1 rep + BM4D	1 rep + AONLM
1	Superior frontal	0.2724±0.0536	0.1692±0.03157	0.129±0.01805	0.1082±0.01406	0.09206±0.01484	0.1485±0.02164	0.168±0.02684	0.1669±0.02786
2	Rostral middle frontal	0.1977±0.07068	0.1252±0.03976	0.09743±0.02443	0.0831±0.02133	0.07218±0.02121	0.1172±0.02972	0.1311±0.03322	0.1271±0.03226
3	Caudal middle frontal	0.2647±0.06135	0.1636±0.03242	0.1211±0.01899	0.09885±0.01269	0.08617±0.01592	0.1397±0.01954	0.1533±0.02307	0.1531±0.02558
4	Pars opercularis	0.2544±0.07431	0.1517±0.03902	0.11±0.02165	0.09073±0.01774	0.077±0.01745	0.1235±0.02539	0.1353±0.02765	0.1352±0.02928
5	Pars triangularis	0.2372±0.1074	0.1502±0.06582	0.1069±0.03371	0.08975±0.02797	0.07695±0.02918	0.1206±0.03325	0.133±0.03641	0.1302±0.03755
6	Pars orbitalis	0.2248±0.08882	0.1518±0.05481	0.1165±0.0354	0.09857±0.03102	0.08235±0.02642	0.1425±0.04126	0.1535±0.04307	0.1489±0.04144
7	Lateral orbitofrontal	0.2732±0.06782	0.1841±0.04273	0.1381±0.02464	0.1175±0.02447	0.09621±0.01819	0.1544±0.03255	0.1691±0.03208	0.1717±0.03445
8	Medial orbitofrontal	0.2302±0.0599	0.1605±0.03942	0.13±0.0301	0.1101±0.02623	0.09281±0.02129	0.1492±0.03357	0.157±0.03212	0.1587±0.03261
9	Precentral	0.33±0.05801	0.2106±0.0352	0.1655±0.02341	0.1374±0.01881	0.1204±0.0205	0.1835±0.03179	0.2068±0.04857	0.2135±0.0479
10	Paracentral	0.3474±0.05652	0.2146±0.03067	0.1687±0.02053	0.1419±0.01826	0.1231±0.02151	0.1905±0.02711	0.2162±0.05089	0.2287±0.05571
11	Frontal pole	0.2304±0.0875	0.1612±0.05737	0.1396±0.04845	0.1154±0.03685	0.107±0.04082	0.1659±0.06649	0.194±0.07748	0.1794±0.07227
12	Superior parietal	0.2165±0.04414	0.1303±0.01554	0.1018±0.009543	0.08448±0.006521	0.07332±0.009185	0.1235±0.01562	0.1387±0.02022	0.1396±0.01839
13	Inferior parietal	0.183±0.03884	0.1148±0.01074	0.09062±0.006357	0.07635±0.005439	0.06773±0.008305	0.1125±0.01452	0.1255±0.0205	0.1232±0.0188
14	Supramarginal	0.1982±0.0372	0.1247±0.02024	0.09831±0.01181	0.08271±0.01015	0.07243±0.01124	0.1194±0.01627	0.1315±0.02106	0.1294±0.02088
15	Postcentral	0.2642±0.04854	0.1696±0.03413	0.1317±0.0239	0.1108±0.02018	0.09446±0.01912	0.1592±0.02723	0.1811±0.03708	0.1821±0.03282
16	Precuneus	0.2193±0.04294	0.1307±0.01409	0.1022±0.008607	0.0828±0.005642	0.07241±0.008587	0.1215±0.01296	0.1371±0.01762	0.1411±0.01781
17	Superior temporal	0.2593±0.03898	0.1726±0.02397	0.1315±0.01443	0.1144±0.01525	0.09869±0.01894	0.1555±0.01925	0.1662±0.0186	0.1665±0.01921
18	Middle temporal	0.2215±0.03958	0.144±0.02022	0.111±0.01282	0.09557±0.01214	0.08252±0.0128	0.1375±0.0191	0.1496±0.02422	0.1473±0.02215
19	Inferior temporal	0.2412±0.04746	0.1554±0.02683	0.122±0.01598	0.1045±0.01665	0.08684±0.01378	0.1526±0.02744	0.1618±0.02542	0.1643±0.02768
20	Banks of sup temp sulcus	0.1894±0.03193	0.1153±0.0147	0.08612±0.005842	0.07122±0.005444	0.05917±0.006335	0.09891±0.01159	0.1115±0.01577	0.1099±0.01658
21	Fusiform	0.2463±0.05098	0.1546±0.03042	0.1196±0.01901	0.09856±0.014	0.08318±0.01684	0.1451±0.02223	0.1566±0.0217	0.1619±0.02429
22	Transverse temporal	0.3646±0.07071	0.2309±0.05088	0.1799±0.03548	0.1396±0.03033	0.1224±0.02988	0.204±0.0425	0.2192±0.05211	0.2423±0.04297
23	Entorhinal	0.3434±0.06467	0.2577±0.08661	0.2046±0.04682	0.1725±0.03008	0.1477±0.02886	0.2442±0.04564	0.2839±0.05642	0.2853±0.06142
24	Temporal pole	0.3374±0.06953	0.252±0.06244	0.2046±0.0486	0.1732±0.03477	0.143±0.02987	0.2444±0.05361	0.3052±0.07984	0.3003±0.07335
25	Parahippocampal	0.2913±0.05749	0.192±0.03799	0.1455±0.01961	0.1266±0.01905	0.1086±0.01845	0.167±0.02443	0.1936±0.02066	0.1936±0.0291
26	Insula	0.3808±0.05685	0.2648±0.03606	0.2082±0.02442	0.1774±0.0183	0.1555±0.02039	0.2568±0.02525	0.3028±0.03278	0.3158±0.03693
27	Lateral occipital	0.1969±0.03237	0.1251±0.01119	0.1016±0.008153	0.08696±0.008086	0.07763±0.007071	0.1489±0.0266	0.1594±0.02523	0.1505±0.02395
28	Lingual	0.2352±0.03415	0.1624±0.01964	0.1348±0.01657	0.1168±0.01676	0.103±0.01289	0.2157±0.03783	0.2265±0.04672	0.2282±0.0414
29	Cuneus	0.2169±0.04204	0.1433±0.01586	0.122±0.01576	0.1037±0.0135	0.09455±0.01412	0.1791±0.03972	0.189±0.03014	0.1797±0.02911
30	Pericalcarine	0.2432±0.03715	0.1708±0.02007	0.1444±0.02321	0.1285±0.02209	0.1181±0.02442	0.2444±0.05763	0.2452±0.0581	0.2351±0.04442
31	Rostral anterior cingulate	0.3113±0.07176	0.1987±0.04196	0.1517±0.03522	0.1219±0.02441	0.1028±0.01943	0.1596±0.03249	0.1675±0.03063	0.1692±0.02938
32	Caudal anterior cingulate	0.2847±0.05613	0.1869±0.0353	0.1376±0.01828	0.1121±0.01195	0.09756±0.01809	0.1487±0.02033	0.1574±0.02267	0.1572±0.02259
33	Posterior cingulate	0.3±0.04635	0.1798±0.03109	0.1306±0.01324	0.1064±0.01108	0.09014±0.01407	0.1452±0.02111	0.1552±0.0195	0.1604±0.01883
34	Isthmus cingulate	0.3189±0.07067	0.2002±0.03621	0.1539±0.02359	0.127±0.01811	0.1099±0.02011	0.1734±0.02555	0.1886±0.0248	0.1925±0.02475
35	Whole brain	0.2471±0.04139	0.1578±0.02556	0.1229±0.01523	0.1033±0.01237	0.08925±0.01333	0.1493±0.02013	0.1647±0.02477	0.165±0.02452

Supplementary Table 1. Gray–white surface displacement. The group mean and standard deviation of the mean absolute displacement of the gray–white surface estimated from the images from the single-repetition data, 2- to 5-repetition averaged data and the single-repetition data denoised by DnCNN, BM4D and AONLM compared to the images from the 6-repetition averaged data across 30 image volumes from the 5 evaluation subjects, calculated for 34 cortical parcels (left and right hemispheres combined) from the Desikan-Killiany Atlas provided by FreeSurfer and for the whole brain.

Gray-CSF surface displacement (mm) compared to ground truth from 6-repetition averaged data									
#	Cortices	1 repetition	2 repetitions	3 repetitions	4 repetitions	5 repetitions	1 rep + DnCNN	1 rep + BM4D	1 rep + AONLM
1	Superior frontal	0.1913±0.04444	0.1207±0.02437	0.09649±0.01568	0.08558±0.01537	0.07352±0.01393	0.1232±0.02731	0.1534±0.04332	0.1388±0.03301
2	Rostral middle frontal	0.1946±0.05661	0.1198±0.03456	0.09838±0.02835	0.08698±0.02634	0.07622±0.02587	0.1366±0.04473	0.1823±0.07096	0.1579±0.05555
3	Caudal middle frontal	0.1603±0.0349	0.09986±0.0206	0.07789±0.01208	0.06847±0.01274	0.06001±0.01312	0.1036±0.0233	0.1189±0.03143	0.1102±0.02552
4	Pars opercularis	0.1654±0.03633	0.1043±0.01871	0.08358±0.01365	0.07083±0.0108	0.05961±0.01147	0.1116±0.02648	0.1262±0.02771	0.1194±0.02401
5	Pars triangularis	0.1698±0.05536	0.1046±0.02718	0.08333±0.02012	0.07253±0.01886	0.06245±0.02091	0.116±0.03349	0.145±0.05354	0.1283±0.03999
6	Pars orbitalis	0.1882±0.06619	0.1172±0.04062	0.09308±0.0301	0.08197±0.02991	0.07138±0.02999	0.1346±0.04962	0.1732±0.06938	0.1527±0.05666
7	Lateral orbitofrontal	0.2512±0.04223	0.1719±0.03047	0.1382±0.02319	0.1216±0.01951	0.09782±0.01619	0.1873±0.04114	0.2231±0.0538	0.2089±0.04156
8	Medial orbitofrontal	0.2684±0.05152	0.1853±0.02753	0.158±0.03127	0.1378±0.02747	0.1139±0.02364	0.2077±0.04553	0.236±0.06363	0.2208±0.04691
9	Precentral	0.1532±0.02725	0.0992±0.01726	0.08069±0.01505	0.06877±0.01283	0.05789±0.009577	0.0967±0.01662	0.1067±0.02339	0.1011±0.01729
10	Paracentral	0.1569±0.0348	0.09981±0.02037	0.07765±0.01613	0.06533±0.01382	0.0554±0.01059	0.1021±0.01956	0.1117±0.02158	0.1086±0.02198
11	Frontal pole	0.2384±0.07801	0.1562±0.04237	0.1487±0.05193	0.1229±0.04512	0.1192±0.0386	0.1739±0.05222	0.241±0.08651	0.2052±0.06352
12	Superior parietal	0.1539±0.03881	0.09713±0.01508	0.07764±0.01368	0.06789±0.01127	0.05969±0.0107	0.09971±0.02567	0.1141±0.03445	0.1054±0.03025
13	Inferior parietal	0.1563±0.03094	0.09765±0.0115	0.07842±0.008508	0.06813±0.008158	0.06141±0.01181	0.1092±0.02103	0.1266±0.03087	0.1167±0.02781
14	Supramarginal	0.1674±0.04344	0.1096±0.02416	0.0874±0.01404	0.07738±0.01405	0.06672±0.01428	0.1149±0.02314	0.1317±0.03241	0.1213±0.0244
15	Postcentral	0.1295±0.02017	0.08505±0.01062	0.06702±0.008854	0.05779±0.006189	0.04923±0.006239	0.0866±0.01395	0.09757±0.01998	0.0916±0.01596
16	Precuneus	0.1673±0.0326	0.1061±0.01546	0.08349±0.01133	0.07014±0.008038	0.06049±0.008582	0.1117±0.02195	0.1274±0.02823	0.121±0.02483
17	Superior temporal	0.2206±0.04574	0.1575±0.03521	0.124±0.02138	0.1113±0.02306	0.09833±0.02499	0.154±0.02904	0.1686±0.03683	0.1603±0.03431
18	Middle temporal	0.2326±0.05577	0.1587±0.04203	0.123±0.02847	0.1076±0.02311	0.09471±0.03011	0.1631±0.0419	0.1797±0.04698	0.1687±0.04635
19	Inferior temporal	0.2876±0.06326	0.1966±0.05414	0.1547±0.02971	0.1363±0.03134	0.1107±0.02741	0.2037±0.05935	0.2129±0.04838	0.2025±0.04408
20	Banks of sup temp sulcus	0.1831±0.03068	0.125±0.04315	0.09274±0.00744	0.0782±0.006199	0.0654±0.007666	0.1273±0.01958	0.1462±0.02918	0.1357±0.02035
21	Fusiform	0.2506±0.0492	0.1701±0.0397	0.1339±0.02693	0.114±0.02388	0.09615±0.02407	0.1708±0.03484	0.1823±0.03444	0.1799±0.03402
22	Transverse temporal	0.2191±0.05948	0.1489±0.04053	0.1261±0.03432	0.1043±0.03193	0.0918±0.02803	0.1584±0.04886	0.156±0.03833	0.1571±0.0416
23	Entorhinal	0.4437±0.105	0.3581±0.2666	0.2517±0.06709	0.2154±0.03797	0.1911±0.06227	0.2847±0.0437	0.2902±0.05204	0.2949±0.05644
24	Temporal pole	0.4115±0.12	0.3316±0.1551	0.249±0.06562	0.218±0.0629	0.1839±0.06022	0.2745±0.0688	0.2658±0.04893	0.2574±0.04887
25	Parahippocampal	0.272±0.06648	0.1813±0.04378	0.1419±0.0317	0.1236±0.03232	0.1011±0.02358	0.1844±0.0388	0.1968±0.04689	0.1984±0.03872
26	Insula	0.2739±0.03667	0.1973±0.01806	0.1655±0.01239	0.1438±0.00929	0.1282±0.01066	0.1957±0.01948	0.2071±0.0182	0.2103±0.01481
27	Lateral occipital	0.1537±0.02931	0.09403±0.007145	0.07442±0.005717	0.06486±0.005007	0.05775±0.006145	0.1083±0.02076	0.1158±0.02207	0.1107±0.02149
28	Lingual	0.2011±0.0361	0.1272±0.01691	0.1059±0.01661	0.09029±0.01223	0.0802±0.01274	0.1535±0.02342	0.1539±0.02951	0.157±0.0286
29	Cuneus	0.1422±0.02873	0.08665±0.009383	0.07162±0.01121	0.06233±0.007152	0.05506±0.008055	0.09928±0.01603	0.1052±0.01768	0.1026±0.01884
30	Pericalcarine	0.1571±0.03294	0.1017±0.0154	0.08431±0.01782	0.07493±0.01652	0.06826±0.02038	0.1142±0.02938	0.1173±0.0313	0.1173±0.02879
31	Rostral anterior cingulate	0.2588±0.04309	0.1835±0.03033	0.1482±0.02499	0.1292±0.02689	0.1072±0.02067	0.1833±0.03949	0.2113±0.04781	0.1896±0.03269
32	Caudal anterior cingulate	0.2473±0.04066	0.1752±0.01942	0.1427±0.01366	0.123±0.01032	0.1019±0.01064	0.1714±0.02416	0.1834±0.02819	0.1744±0.0237
33	Posterior cingulate	0.2285±0.03216	0.1566±0.01709	0.125±0.01029	0.1058±0.007343	0.08979±0.009166	0.156±0.01967	0.1707±0.02255	0.1653±0.0211
34	Isthmus cingulate	0.2518±0.03012	0.1746±0.0155	0.143±0.008907	0.1211±0.006963	0.1019±0.007722	0.1706±0.02017	0.1795±0.01711	0.1768±0.01901
35	Whole brain	0.1935±0.03284	0.1275±0.01984	0.1021±0.01357	0.08884±0.01161	0.07636±0.01214	0.1337±0.02316	0.1517±0.03209	0.1423±0.02613

Supplementary Table 2. Gray–CSF surface displacement. The group mean and standard deviation of the mean absolute displacement of the gray–CSF surface estimated from the images from the single-repetition data, 2- to 5-repetition averaged data and the single-repetition data denoised by DnCNN, BM4D and AONLM compared to the images from the 6-repetition averaged data across 30 image volumes from the 5 evaluation subjects, calculated for 34 cortical parcels (left and right hemispheres combined) from the Desikan-Killiany Atlas provided by FreeSurfer and for the whole brain.

Cortical thickness difference (mm) compared to ground truth from 6-repetition averaged data									
#	Cortices	1 repetition	2 repetitions	3 repetitions	4 repetitions	5 repetitions	1 rep + DnCNN	1 rep + BM4D	1 rep + AONLM
1	Superior frontal	0.1853±0.03055	0.1186±0.02105	0.09382±0.01344	0.08042±0.01117	0.06817±0.01079	0.1214±0.02253	0.1499±0.03158	0.1373±0.02657
2	Rostral middle frontal	0.1631±0.04248	0.1009±0.02796	0.08117±0.02128	0.06981±0.01771	0.05943±0.01533	0.1121±0.03357	0.1384±0.04659	0.1253±0.03917
3	Caudal middle frontal	0.1748±0.03459	0.1116±0.02328	0.08574±0.01335	0.07274±0.01203	0.06092±0.01087	0.1112±0.02092	0.1303±0.02641	0.1239±0.02395
4	Pars opercularis	0.1714±0.0379	0.1063±0.02142	0.08087±0.01459	0.06865±0.0119	0.05729±0.009922	0.107±0.02624	0.1203±0.02687	0.116±0.02429
5	Pars triangularis	0.172±0.06022	0.1079±0.0393	0.08104±0.02311	0.06843±0.01959	0.05813±0.01807	0.1077±0.03285	0.1289±0.04786	0.1196±0.03938
6	Pars orbitalis	0.1683±0.04852	0.1111±0.03545	0.0875±0.0284	0.07326±0.02176	0.06187±0.01856	0.1207±0.03792	0.1425±0.05234	0.1306±0.0429
7	Lateral orbitofrontal	0.203±0.03651	0.141±0.02708	0.112±0.01909	0.09671±0.01592	0.0787±0.01252	0.1514±0.03095	0.1775±0.04205	0.1705±0.03593
8	Medial orbitofrontal	0.2003±0.03826	0.1416±0.02494	0.121±0.02194	0.1031±0.0182	0.08639±0.01666	0.1628±0.03482	0.18±0.04679	0.1752±0.03646
9	Precentral	0.1922±0.03063	0.1264±0.01884	0.1014±0.01442	0.08396±0.011	0.07186±0.01153	0.1325±0.02406	0.1493±0.03568	0.1528±0.03431
10	Paracentral	0.1986±0.0269	0.1295±0.01957	0.1025±0.01324	0.08482±0.01074	0.07088±0.01206	0.1395±0.02098	0.1539±0.03789	0.1625±0.03939
11	Frontal pole	0.1861±0.05158	0.1253±0.03208	0.1114±0.03126	0.09341±0.02309	0.08576±0.01941	0.1496±0.04203	0.1839±0.06527	0.1615±0.04754
12	Superior parietal	0.1491±0.02225	0.09529±0.01024	0.07489±0.006546	0.06361±0.004999	0.05417±0.005375	0.1041±0.02195	0.1183±0.02581	0.1142±0.02263
13	Inferior parietal	0.1397±0.02422	0.08831±0.009968	0.07041±0.005213	0.06014±0.005024	0.05274±0.005975	0.0965±0.01778	0.1119±0.02005	0.1066±0.02054
14	Supramarginal	0.1485±0.03003	0.09654±0.01706	0.07699±0.01058	0.0663±0.008693	0.05666±0.008479	0.1019±0.01817	0.1159±0.0227	0.1096±0.01876
15	Postcentral	0.1665±0.02588	0.1092±0.01778	0.08545±0.01273	0.07156±0.01021	0.05974±0.009252	0.1175±0.02093	0.1335±0.02838	0.1337±0.02467
16	Precuneus	0.1488±0.02005	0.09779±0.01061	0.07796±0.007576	0.06417±0.005039	0.05462±0.005488	0.1044±0.01512	0.1199±0.01846	0.119±0.01758
17	Superior temporal	0.1912±0.02614	0.133±0.02027	0.1047±0.01179	0.09284±0.01161	0.07931±0.01318	0.1332±0.01916	0.1487±0.02502	0.1425±0.02208
18	Middle temporal	0.1845±0.03134	0.1273±0.02497	0.1014±0.01732	0.08789±0.01388	0.07544±0.01631	0.1346±0.02815	0.1538±0.03099	0.1462±0.02955
19	Inferior temporal	0.2074±0.04201	0.1461±0.03331	0.1166±0.01991	0.1016±0.02024	0.08295±0.01691	0.1599±0.04164	0.1738±0.03635	0.1646±0.03358
20	Banks of sup temp sulcus	0.155±0.02527	0.1023±0.0263	0.0763±0.00614	0.06423±0.004637	0.0536±0.005343	0.1055±0.01555	0.1218±0.02029	0.1139±0.01642
21	Fusiform	0.1926±0.03602	0.136±0.02807	0.1069±0.01987	0.09074±0.01791	0.07546±0.01684	0.1387±0.02418	0.1572±0.0279	0.155±0.02842
22	Transverse temporal	0.2331±0.0421	0.1492±0.03417	0.1154±0.02583	0.0932±0.02032	0.08142±0.01675	0.1483±0.02395	0.154±0.02554	0.1657±0.02443
23	Entorhinal	0.3209±0.07421	0.2632±0.1661	0.1881±0.05271	0.1585±0.02637	0.1416±0.03688	0.2265±0.04005	0.2367±0.05287	0.2367±0.05558
24	Temporal pole	0.2957±0.08222	0.2418±0.1101	0.1869±0.04348	0.1599±0.03715	0.1379±0.03905	0.2201±0.05038	0.2372±0.05409	0.2288±0.05605
25	Parahippocampal	0.2255±0.03986	0.1611±0.03048	0.1259±0.02137	0.1108±0.02247	0.09077±0.0186	0.1687±0.03112	0.1859±0.03972	0.1829±0.03407
26	Insula	0.242±0.0318	0.1763±0.01763	0.1456±0.01314	0.126±0.01032	0.1136±0.01147	0.182±0.01983	0.2041±0.02418	0.2057±0.02263
27	Lateral occipital	0.1447±0.02396	0.09005±0.006984	0.07283±0.003932	0.06242±0.003198	0.05505±0.00378	0.1089±0.01737	0.1212±0.01866	0.1153±0.01893
28	Lingual	0.1703±0.02699	0.1165±0.01274	0.09657±0.01102	0.08212±0.008749	0.07114±0.007885	0.1557±0.02316	0.1648±0.03295	0.166±0.0262
29	Cuneus	0.1442±0.02413	0.09269±0.00823	0.07796±0.00646	0.06602±0.005539	0.05728±0.005062	0.118±0.02291	0.1261±0.01881	0.1222±0.02001
30	Pericalcarine	0.1617±0.02855	0.1107±0.01377	0.09247±0.01198	0.08154±0.01136	0.07259±0.01324	0.1669±0.04166	0.1619±0.04207	0.1551±0.03643
31	Rostral anterior cingulate	0.214±0.03345	0.1449±0.02209	0.1152±0.01989	0.09787±0.01866	0.08315±0.01403	0.146±0.03294	0.1647±0.03866	0.1539±0.03146
32	Caudal anterior cingulate	0.1982±0.02901	0.1408±0.01927	0.1143±0.01261	0.097±0.009672	0.08374±0.01348	0.1422±0.01745	0.1507±0.02224	0.1455±0.02152
33	Posterior cingulate	0.1947±0.02562	0.1313±0.01813	0.1034±0.01065	0.08557±0.007924	0.0729±0.008893	0.1345±0.0187	0.1433±0.02052	0.1449±0.02004
34	Isthmus cingulate	0.2176±0.03474	0.1465±0.01827	0.1189±0.01218	0.1007±0.009819	0.08355±0.01006	0.1493±0.01937	0.1559±0.01735	0.1571±0.02014
35	Whole brain	0.1761±0.02746	0.1171±0.01801	0.09334±0.01196	0.07959±0.009615	0.06773±0.00934	0.1261±0.02026	0.1434±0.02681	0.1383±0.02349

Supplementary Table 3. Cortical thickness difference. The group mean and standard deviation of the mean absolute difference of the cortical thickness estimated from the images from the single-repetition data, 2- to 5-repetition averaged data and the single-repetition data denoised by DnCNN, BM4D and AONLM compared to the images from the 6-repetition averaged data across 30 image volumes from the 5 evaluation subjects, calculated for 34 cortical parcels (left and right hemispheres combined) from the Desikan-Killiany Atlas provided by FreeSurfer and for the whole brain.

Scan-rescan precision										
#	Cortices	Gray-white surface displacement (mm)			Gray-CSF surface displacement (mm)			Cortical thickness difference (mm)		
		1 rep + DnCNN	1 rep + BM4D	1 rep + AONLM	1 rep + DnCNN	1 rep + BM4D	1 rep + AONLM	1 rep + DnCNN	1 rep + BM4D	1 rep + AONLM
1	Superior frontal	0.157±0.04002	0.159±0.04046	0.1659±0.04202	0.1518±0.04321	0.1703±0.04732	0.1665±0.0444	0.1452±0.03596	0.1608±0.03906	0.1595±0.03903
2	Rostral middle frontal	0.1425±0.05495	0.1592±0.05791	0.1621±0.05646	0.18±0.08167	0.2153±0.08891	0.2081±0.08159	0.1394±0.05284	0.1608±0.05442	0.1608±0.05269
3	Caudal middle frontal	0.147±0.03577	0.15±0.03873	0.1586±0.04249	0.1298±0.03596	0.138±0.04208	0.1403±0.03943	0.133±0.03158	0.1426±0.0358	0.1463±0.03562
4	Pars opercularis	0.1382±0.03913	0.1371±0.03691	0.1446±0.03969	0.1426±0.03819	0.143±0.03684	0.1445±0.03545	0.1339±0.03394	0.1376±0.03359	0.1405±0.03507
5	Pars triangularis	0.1403±0.05566	0.1504±0.06056	0.1524±0.05812	0.1505±0.05755	0.1657±0.06702	0.1635±0.06425	0.1323±0.0489	0.1451±0.05364	0.1473±0.05508
6	Pars orbitalis	0.1749±0.07372	0.1893±0.07797	0.1894±0.07512	0.188±0.09946	0.2115±0.09887	0.2058±0.099	0.1546±0.0669	0.1748±0.06852	0.175±0.0693
7	Lateral orbitofrontal	0.1937±0.0651	0.1964±0.0644	0.2015±0.06355	0.2553±0.09246	0.2681±0.09147	0.2669±0.08636	0.1949±0.05837	0.2052±0.05872	0.2077±0.05615
8	Medial orbitofrontal	0.1877±0.05595	0.1887±0.05701	0.1953±0.05423	0.2737±0.09121	0.2817±0.09183	0.2814±0.08638	0.206±0.05959	0.2134±0.06522	0.2158±0.05669
9	Precentral	0.2019±0.04555	0.1941±0.04627	0.2064±0.04806	0.119±0.02472	0.1164±0.0256	0.1203±0.02376	0.1599±0.03272	0.1592±0.03615	0.1689±0.03603
10	Paracentral	0.2125±0.03338	0.1972±0.03643	0.2208±0.04084	0.1288±0.02507	0.1211±0.02566	0.1269±0.02685	0.1713±0.02595	0.1665±0.03158	0.1825±0.03496
11	Frontal pole	0.2133±0.1181	0.2412±0.1165	0.2415±0.1251	0.2369±0.1384	0.2956±0.117	0.2827±0.1149	0.1784±0.07987	0.214±0.08191	0.2148±0.07765
12	Superior parietal	0.138±0.01979	0.1364±0.02123	0.1449±0.02286	0.1192±0.03514	0.1255±0.03961	0.1258±0.03965	0.1238±0.02437	0.1296±0.02686	0.1337±0.02628
13	Inferior parietal	0.1191±0.01762	0.1263±0.02141	0.1311±0.02203	0.1277±0.0292	0.1397±0.03787	0.1389±0.0334	0.114±0.01778	0.1266±0.02381	0.1272±0.02193
14	Supramarginal	0.1285±0.02556	0.1316±0.02738	0.1374±0.02837	0.1387±0.0382	0.147±0.04231	0.1424±0.03633	0.1223±0.02435	0.1325±0.02711	0.131±0.02619
15	Postcentral	0.178±0.0376	0.1724±0.03859	0.1853±0.03925	0.1098±0.02188	0.1094±0.02426	0.1118±0.02179	0.1435±0.0263	0.1437±0.02952	0.1514±0.02882
16	Precuneus	0.1399±0.01962	0.1377±0.0201	0.1452±0.02017	0.1392±0.02875	0.137±0.03378	0.1379±0.03176	0.1321±0.01891	0.1345±0.02144	0.1376±0.02212
17	Superior temporal	0.1646±0.02638	0.1581±0.02687	0.1671±0.03005	0.1856±0.04356	0.183±0.04722	0.1851±0.04347	0.1588±0.02904	0.1662±0.03557	0.1673±0.03314
18	Middle temporal	0.148±0.02896	0.1503±0.0298	0.1564±0.03065	0.1902±0.0642	0.2059±0.07408	0.1996±0.072	0.1608±0.03892	0.1791±0.04963	0.1742±0.04722
19	Inferior temporal	0.1779±0.04484	0.1708±0.0389	0.1786±0.04239	0.2528±0.08932	0.2593±0.09676	0.253±0.0968	0.1951±0.05706	0.2092±0.0642	0.2027±0.06386
20	Banks of sup temp sulcus	0.1115±0.01632	0.1165±0.0205	0.1211±0.01895	0.1571±0.02971	0.1636±0.0388	0.1589±0.02817	0.1313±0.01807	0.1418±0.0248	0.1381±0.01861
21	Fusiform	0.1705±0.03561	0.1617±0.0289	0.1715±0.03161	0.2182±0.06523	0.207±0.06214	0.2095±0.06291	0.1772±0.04459	0.1801±0.04654	0.1799±0.04528
22	Transverse temporal	0.2239±0.04902	0.2251±0.06411	0.2557±0.0556	0.1767±0.04511	0.1559±0.04721	0.1594±0.03628	0.1743±0.02977	0.1789±0.03816	0.1966±0.03589
23	Entorhinal	0.3109±0.07561	0.284±0.05143	0.2988±0.05291	0.3575±0.09264	0.3187±0.1033	0.3445±0.1153	0.2805±0.07655	0.2742±0.07404	0.2781±0.08825
24	Temporal pole	0.3031±0.09927	0.2907±0.1182	0.3064±0.1129	0.3292±0.1547	0.3054±0.1297	0.3276±0.1617	0.2688±0.1027	0.2647±0.1076	0.2886±0.1264
25	Parahippocampal	0.1944±0.03907	0.1615±0.02378	0.1791±0.02739	0.2344±0.0733	0.2121±0.06963	0.2259±0.07579	0.2095±0.05711	0.1997±0.05964	0.2081±0.06089
26	Insula	0.2779±0.05112	0.2631±0.04618	0.261±0.04645	0.232±0.03522	0.2065±0.02563	0.2061±0.02456	0.2103±0.03394	0.2022±0.03098	0.1987±0.02966
27	Lateral occipital	0.1511±0.02218	0.1621±0.02349	0.1639±0.02562	0.1233±0.02559	0.1264±0.02715	0.1288±0.02704	0.1248±0.01818	0.1349±0.02073	0.136±0.02157
28	Lingual	0.2055±0.02287	0.2136±0.02852	0.2243±0.03003	0.1664±0.02971	0.1559±0.02905	0.1641±0.0291	0.1681±0.02101	0.1742±0.02509	0.1803±0.02616
29	Cuneus	0.1719±0.02902	0.1855±0.03175	0.1874±0.03012	0.1098±0.02337	0.1108±0.02402	0.1148±0.02367	0.1286±0.01702	0.1395±0.02138	0.1403±0.01902
30	Pericalcarine	0.211±0.03117	0.2216±0.03522	0.2279±0.03896	0.1248±0.03283	0.1261±0.02955	0.1327±0.03491	0.1608±0.02608	0.1642±0.03376	0.1671±0.03185
31	Rostral anterior cingulate	0.1819±0.05255	0.1788±0.04467	0.1798±0.04353	0.2347±0.08022	0.2372±0.06655	0.2279±0.0626	0.1797±0.05297	0.1857±0.04439	0.1798±0.0465
32	Caudal anterior cingulate	0.1698±0.03529	0.1666±0.03504	0.172±0.03783	0.2103±0.03663	0.1981±0.03693	0.2012±0.03323	0.1702±0.02681	0.1711±0.03071	0.171±0.0303
33	Posterior cingulate	0.172±0.02972	0.161±0.02872	0.1705±0.03047	0.194±0.03335	0.1801±0.03517	0.1854±0.03289	0.1661±0.0294	0.1651±0.03293	0.1655±0.03138
34	Isthmus cingulate	0.1944±0.03594	0.1684±0.02745	0.1797±0.02981	0.1979±0.02761	0.174±0.02661	0.1855±0.02794	0.173±0.02684	0.1544±0.02564	0.1615±0.02692
35	Whole brain	0.1649±0.03371	0.1654±0.0336	0.1726±0.0348	0.1648±0.04283	0.1701±0.0447	0.1702±0.04257	0.1519±0.03158	0.16±0.03421	0.1619±0.0338

Supplementary Table 4. Scan-rescan precision. The group mean and standard deviation of the mean absolute displacement/difference of the gray–white surface, gray–CSF surface and cortical thickness estimated from two consecutively acquired 1-repetition data denoised by DnCNN, BM4D and AONLM across 25 image volumes from the 5 evaluation subjects, calculated for 34 cortical parcels (left and right hemispheres combined) from the Desikan-Killiany Atlas provided by FreeSurfer and for the whole brain.