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Local gyrification in children and adolescents with migraine: a descriptive comparison of conventional and shape-adaptive measures

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ABSTRACT

Background: Local gyrification findings in pediatric migraine may vary according to how cortical folding is measured. We aimed to describe similarities and differences between conventional FreeSurfer-derived and shape-adaptive Lyu measures in patient-control comparisons and comparisons based on sex, age, migraine frequency, and associated symptoms.

Methods: Comparisons addressed diagnosis, sex and age within both groups, and monthly migraine days (MMDs; <8 *vs.* ≥8), photophobia and/or phonophobia, and nausea and/or vomiting within patients. Both measures were assessed using Permutation Analysis of Linear Models (PALM) with threshold-free cluster enhancement (TFCE) and family-wise error (FWE) correction. Findings were compared according to statistical significance, effect direction, and anatomical distribution.

Results: Both measures identified lower local gyrification in patients than in healthy controls and in female than in male patients, with different anatomical and hemispheric distributions. Among healthy controls, only the conventional measure identified lower gyrification in females than in males. Neither measure identified significant differences in age-related comparisons or comparisons based on migraine frequency or associated symptoms.

Conclusions: The two gyrification measures agreed in effect direction for selected contrasts but differed in anatomical localization. These descriptive findings do not establish spatial concordance, methodological superiority, or a specific cortical signature of pediatric migraine. Harmonized comparisons and independent validation are required.

Key words: migraine; children and adolescents; local gyrification; cortical folding; MRI; morphometry; sex.

Introduction

Migraine is a common neurological disorder in children and adolescents, characterized by recurrent headache attacks accompanied by sensory, autonomic, affective, and cognitive symptoms. (1,2) Structural magnetic resonance imaging (MRI) studies have reported abnormalities in cortical thickness, gray-matter volume, surface morphology, and cortical folding. (2-4) However, the anatomical literature remains heterogeneous, and no single reproducible structural signature of migraine has been established. (4-6)

This issue is particularly relevant during childhood and adolescence, when ongoing brain maturation may interact with disease-related processes. (2,7) Different morphometric measures capture partly distinct dimensions of cortical organization. Cortical thickness changes substantially across development, (8) whereas cortical folding is established earlier and is generally considered a relatively more stable feature of cortical architecture. (9,10) Morphometric similarity mapping provides a complementary network-level perspective by integrating multiple MRI-derived features across cortical regions. (11,12) Our previous studies identified diagnosis-, sex-, age-, and symptom-related differences in regional cortical morphology and morphometric similarity networks in children and adolescents with migraine. (10,13)

Local gyrification measures quantify cortical folding by relating the area of the folded cortical surface to that of a corresponding enclosing outer surface. The conventional approach introduced by Schaer *et al.* and implemented in FreeSurfer uses a predefined spherical neighborhood to identify corresponding surface patches. (9) Its standardized implementation facilitates its application across studies, but the neighborhood may encompass adjacent folds and limit the anatomical specificity of local estimates. The shape-adaptive approach proposed by Lyu *et al.* instead adapts the neighborhood to local cortical geometry, elongating along gyral crowns and sulcal fundi. (14) This may allow more localized sampling of individual folds, although the estimates depend on kernel size, anisotropy, and the extraction of sulcal and gyral curves. Both approaches depend on the quality of cortical surface reconstruction. Their different neighborhood definitions may influence the localization and extent of group differences, without implying that either approach is universally more accurate.

The present study was designed as a retrospective methodological reappraisal of local gyrification outputs obtained with conventional FreeSurfer-derived and shape-adaptive Lyu measures in the same participants.

The primary aim was to compare whether the two measures identified differences between patients with migraine without aura and healthy controls. We also examined sex- and age-related differences within the patient and control groups, and

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differences associated with monthly migraine days (MMDs), the presence *vs.* absence of photophobia and/or phonophobia, and the presence *vs.* absence of nausea and/or vomiting. The comparison focused on the presence, direction, and anatomical distribution of the reported findings. Previously published Lyu results were distinguished from additional archived conventional gyrification outputs. (10)

Results

Study population. In the original recruitment process, 201 individuals aged 6-18 years with high-quality MRI examinations were identified from the institutional imaging archive. After application of clinical and imaging eligibility criteria, 80 patients with migraine without aura underwent confirmatory neurological assessment, and 72 were included in the final imaging cohort. (10)

The study cohort consisted of 72 children and adolescents with episodic migraine without aura and 82 healthy controls. Age and sex distributions did not differ significantly between groups (both p=0.2). (10) Demographic and clinical characteristics, including age, sex, age subgroup, MMD category, photophobia or phonophobia, and nausea or vomiting, are summarized in **Table 1**.

A summary of the findings across all contrasts for both gyrification measures, following Permutation Analysis of Linear Models (PALM)/threshold-free cluster enhancement (TFCE) inference with family-wise error (FWE) correction for multiple comparisons, is provided in **Table 2**.

Table 1. Demographic and clinical characteristics.

Characteristic	Migraine patients (n=72)	Healthy controls (n=82)
Age, years, mean ± SD	11.73±3.19	10.96±3.75
Female/male, n	42/30	41/41
Age <12 years, n	42	46
Age ≥12 years, n	30	36
MMDs <8, n	42	-
MMDs ≥8, n	30	-
Photophobia and/or phonophobia, n	62	-
Neither photophobia nor phonophobia, n	10	-
Nausea and/or vomiting, n	38	-
Neither nausea nor vomiting, n	34	-

SD, standard deviation; MMDs, monthly migraine days.

Table 2. Summary of local gyrification findings across clinical comparisons. Results obtained with the shape-adaptive Lyu and conventional FreeSurfer-derived measures are summarized according to statistical significance, effect direction, and anatomical distribution. Only PALM/TFCE results meeting the FWE-corrected significance threshold of p<0.05 are classified as significant. Anatomical descriptions of conventional findings are based on visual inspection of the cortical maps.

Comparison	Shape-adaptive (Lyu)	Conventional FreeSurfer-derived	Descriptive interpretation
Patients *vs.* controls	Significant: patients < controls in left superior and inferior parietal regions, including the supramarginal region	Significant: patients < controls in a spatially restricted right superior parietal focus	Both significant: patients < controls, with different anatomical and hemispheric distributions
Female *vs.* male patients	Significant: females < males in right superior, middle and transverse temporal, postcentral and supramarginal regions	Significant: females < males in left lateral temporal-perisylvian and medial cortical regions	Both significant: females < males, with different anatomical and hemispheric distributions
Female *vs.* male healthy controls	Not significant	Significant: females < males in bilateral inferomedial temporal regions	Significant with the conventional measure only
Age <12 *vs.* ≥12 years within patients	Not significant	Not significant	No significant finding with either measure
Age <12 *vs.* ≥12 years within controls	Not significant	Not significant	No significant finding with either measure
Patients *vs.* controls aged <12 years	Not significant	Not significant	No significant finding with either measure
Patients *vs.* controls aged ≥12 years	Not significant	Not significant	No significant finding with either measure
MMDs <8 *vs.* ≥8	Not significant	Not significant	No significant finding with either measure
Photophobia and/or phonophobia *vs.* neither	Not significant	Not significant	No significant finding with either measure
Nausea and/or vomiting *vs.* neither	Not significant	Not significant	No significant finding with either measure

MMDs, monthly migraine days.

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Local gyrification differences between patients and healthy controls. Both gyrification measures identified significantly lower local gyrification in patients than in healthy controls, with different anatomical and hemispheric distributions (**Figure 1**). The shape-adaptive Lyu measure identified differences in the left superior parietal and supramarginal regions (mean regional p=0.01 for each) and the left inferior parietal region (mean regional p=0.02), as previously reported. (10) The conventional FreeSurfer-derived measure identified a spatially restricted right-hemisphere focus, visually localized to the superior parietal region (FWE-corrected p<0.05). The measures thus agreed in effect direction but identified differences in distinct cortical locations. No quantitative assessment of spatial overlap or comparison of effect sizes was performed.

Local gyrification differences between females and males. Among patients, both gyrification measures identified significantly lower local gyrification in females than in males, with different anatomical and hemispheric distributions (**Figure 2 A-C**). The shape-adaptive Lyu measure identified differences in the right superior and transverse temporal gyri (p<0.04 for each), middle temporal gyrus, postcentral gyrus, and supramarginal gyrus (p<0.05 for each). (10) The conventional FreeSurfer-derived measure identified differences in left lateral temporal-perisylvian and medial cortical regions (p<0.05). The measures therefore agreed in effect direction but differed in anatomical location.

Among healthy controls, the Lyu measure identified no significant sex-related differences, whereas the conventional measure identified lower local gyrification in females than in males in bilateral inferomedial temporal regions (p<0.05; **Figure 2 D-F**). Anatomical descriptions of the conventional findings were based on visual inspection of the cortical maps.

Local gyrification differences between age groups. Neither the shape-adaptive Lyu measure nor the conventional FreeSurfer-derived measure identified significant local gyrification differences between participants aged <12 and ≥12 years within either the patient or healthy control group after PALM/TFCE inference with FWE correction for multiple comparisons. Comparisons between patients and healthy controls within each age group also revealed no significant differences with either measure.

Local gyrification differences by migraine frequency and associated symptoms. Neither the shape-adaptive Lyu measure nor the conventional FreeSurfer-derived measure identified significant local gyrification differences between patients with <8 *vs.* ≥8 MMDs, between those with photophobia and/or phonophobia (n=62) *vs.* neither symptom (n=10), or between those with nausea and/or vomiting (n=38) *vs.* neither symptom (n=34).

Discussion

The present methodological reappraisal provides a descriptive comparison of local gyrification findings obtained using conventional FreeSurfer-derived and shape-adaptive Lyu measures. Both approaches identified lower local gyrification in patients than in healthy controls and in female than in male patients, although their anatomical and hemispheric distributions differed.

Among healthy controls, significantly lower local gyrification in females than in males was identified only with the conventional measure. Neither measure identified significant differences in the age-related comparisons or those based on MMDs, photophobia and/or phonophobia, or nausea and/or vomiting. These observations indicate agreement in effect direction for selected contrasts, but do not establish spatial concordance, methodological equivalence, or a specific cortical signature of pediatric migraine.

The aim was not to identify a superior gyrification method, but to describe similarities and differences between conventional and shape-adaptive gyrification findings. Agreement in effect direction, alongside differences in anatomical distribution, is compatible with the possibility that the two measures capture partly distinct aspects of local folding. The present findings do not establish methodological equivalence, the superiority of either approach, or whether the observed differences arise from the gyrification algorithms themselves.

The conventional FreeSurfer-derived approach estimates folding within a predefined geometrical neighborhood, whereas the shape-adaptive method proposed by Lyu *et al.* adapts the kernel to the individual geometry of gyral crowns and sulcal fundi. (9,14) These approaches therefore quantify related but not identical properties of cortical folding. A predefined neighbor-

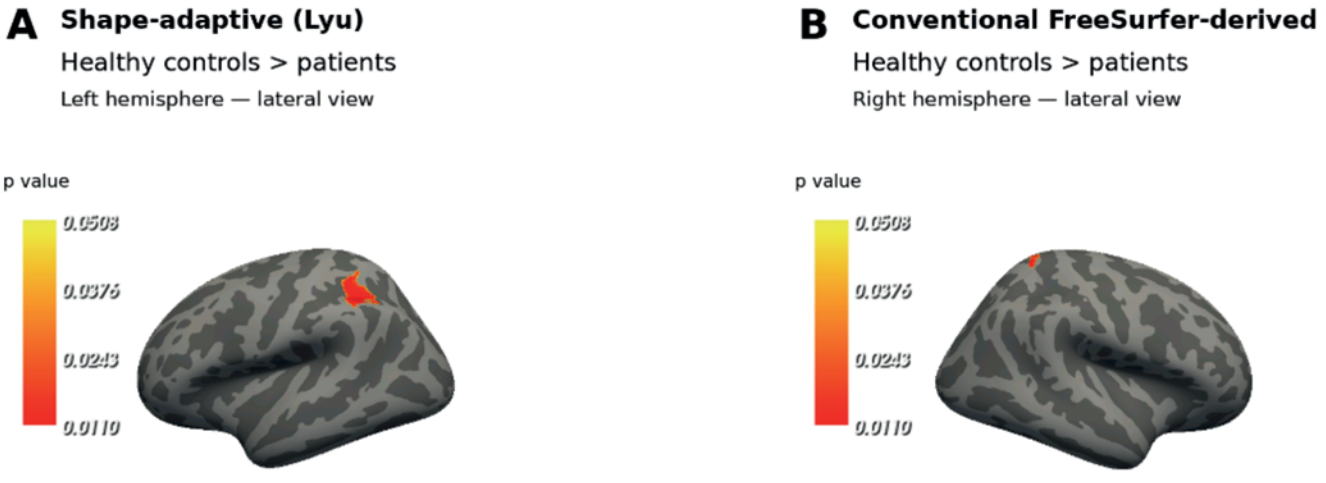


Figure 1. Local gyrification differences between patients with migraine without aura and healthy controls. A) Shape-adaptive Lyu measure showing lower local gyrification in patients in the left parietal region, viewed from the lateral surface. B) Conventional FreeSurfer-derived measure showing lower local gyrification in patients in a spatially restricted right-hemisphere region, viewed from the lateral surface. Color scales indicate FWE-corrected p-values obtained using PALM with TFCE.

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hood may combine information from adjacent folds, whereas an adaptive kernel may sample these structures differently.

Differences in kernel geometry and spatial scale could consequently influence the localization and extent of the measured effects. (14-17) Exact spatial correspondence should therefore not necessarily be expected, although anatomical differences alone cannot establish that either measure is more accurate.

A relevant methodological comparison was the use of conventional FreeSurfer and shape-adaptive gyrification measures to patients with chronic schizophrenia and healthy controls. Both approaches identified group differences, but their regional distributions and cluster sizes differed, with smaller and more widely distributed clusters obtained using the adaptive approach. This illustrates how the representation of group differences can vary between gyrification measures in another clinical population. (18)

The diagnosis-related findings illustrate agreement in effect direction alongside differences in anatomical localization. Diagnosis-related folding patterns were detectable with both approaches, although spatial extent and topography differed. The shape-adaptive measure identified lower gyrification in left superior and inferior parietal regions in patients with migraine, whereas conventional FreeSurfer-derived outputs showed a spatially restricted right-hemisphere focus, visually localized to the superior parietal region. Thus, the direction of the group difference was shared, but its anatomical localization was not. Differences in the cortical geometry sampled by each kernel and in the spatial properties of the resulting measures are possible explanations. Local averaging may attenuate a spatially restricted difference or extend its apparent distribution across adjacent cortical territories. However, these possibilities were not directly tested, and the hemispheric discrepancy cannot be resolved from the available findings. The small conventional focus should also be interpreted proportionately, because statistical significance alone does not establish effect magnitude or clinical relevance.

More broadly, structural MRI studies in migraine have reported heterogeneous cortical findings across populations, acquisition protocols, preprocessing pipelines, and statistical strategies. (19-23) Our observation should therefore be interpreted within specific population and analytical context, rather than as evidence of a fixed disease-specific neuroanatomical pattern.

Sex-related findings similarly illustrate the distinction between agreement in direction and agreement in localization. Among patients, both measures identified lower local gyrification in females than in males. However, the shape-adaptive differences involved right temporal, postcentral, and supramarginal regions, whereas conventional differences involved left lateral temporal-perisylvian and medial cortical regions. Among healthy controls, only the conventional measure identified significant differences, involving bilateral inferomedial temporal regions.

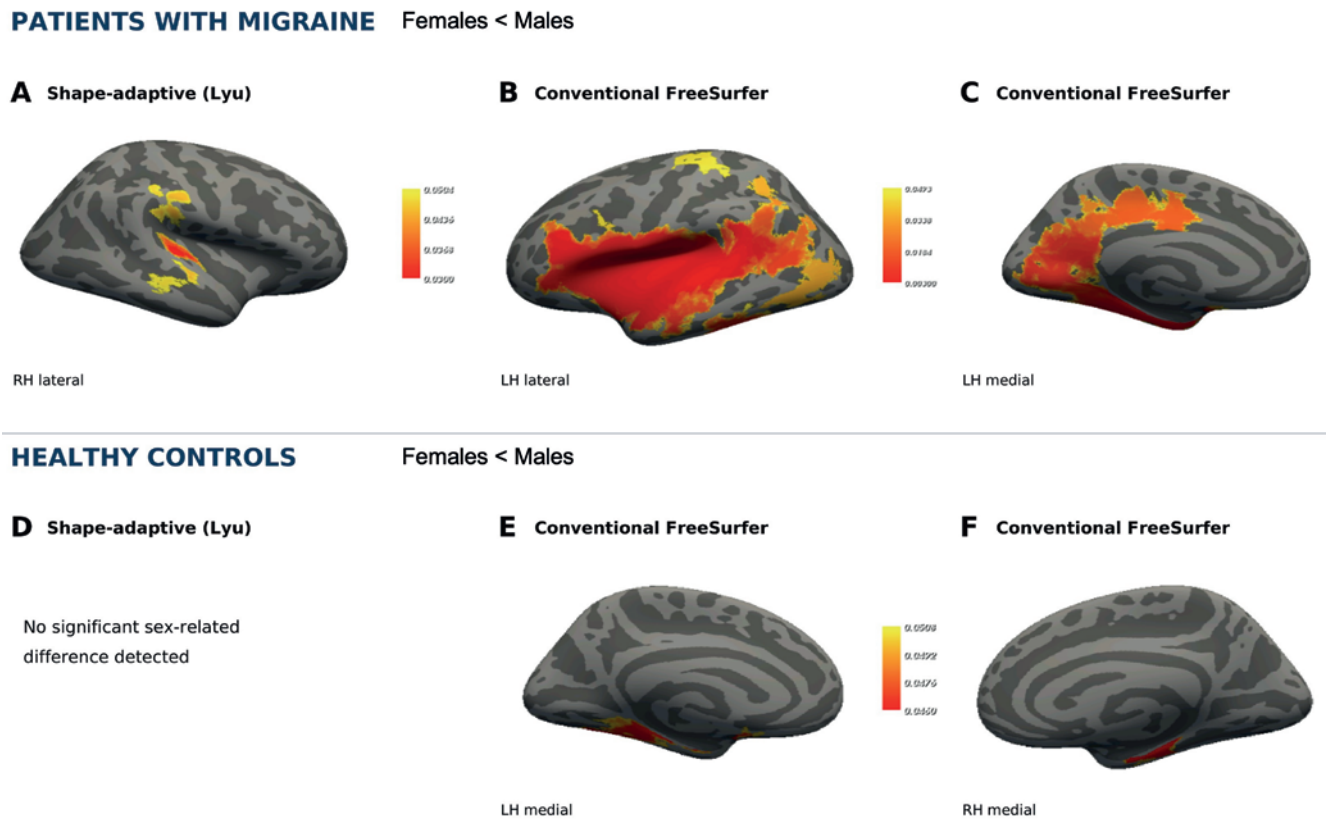


Figure 2. Sex-related differences in local gyrification in patients with migraine and healthy controls. Brain regions showing significantly lower local gyrification in females compared with males, assessed using the shape-adaptive method proposed by Lyu and the conventional FreeSurfer method. A-C) Sex-related differences in patients with migraine. The shape-adaptive method (A) identified significant differences in the right hemisphere (lateral view), whereas the conventional FreeSurfer method revealed more extensive differences in the left hemisphere, shown in lateral (B) and medial (C) views. D-F) Sex-related differences in healthy controls. No significant differences were detected using the shape-adaptive method (D). In contrast, the conventional FreeSurfer method identified localized differences in the medial temporal regions of the left (E) and right (F) hemispheres. Colored regions indicate significantly lower local gyrification in females than in males.

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These observations suggest that sex deserves consideration in developmental gyrification studies, but do not establish a common anatomical pattern across measures or a migraine-specific sex effect. Sex is an important source of biological and clinical heterogeneity during development, and cortical maturation follows sex-specific trajectories partly. (20,21,24)

Cortical maturation itself follows partly sex-specific trajectories involving both cortical thickness and folding, (17) which may interact with migraine-related biology. Hormonal, maturational, and neurodevelopmental factors may therefore contribute to the emergence of sex-dependent structural patterns, although these mechanisms cannot be directly addressed by the present dataset.

Neither measure identified significant differences between the age groups or between patients and controls within either age group. These findings do not establish that gyrification is unrelated to development. Although most major cortical folds are established prenatally, regional modifications continue during childhood and adolescence. (16,19,22,25) Developmental associations may be gradual, nonlinear, and regionally heterogeneous, and may therefore be difficult to detect through a division into two age categories. The present observations provide no evidence of differences between the selected groups, rather than evidence of an absence of developmental change.

Similarly, no significant gyrification differences were identified according to MMDs, photophobia and/or phonophobia, or nausea and/or vomiting. These results do not support a local gyrification correlate of these clinical categories in the present sample. They do not, however, exclude associations with disease burden or associated symptoms. Migraine frequency may vary over time, whereas cortical folding may reflect developmental characteristics. Furthermore, the distributed sensory and autonomic processes implicated in migraine (26-30) may not be adequately represented by a single local surface metric. These are possible explanations for the negative findings and require direct investigation.

The clinical implications of these findings remain limited. Group-level gyrification differences do not establish whether either measure can provide useful information for an individual patient's diagnosis, prognosis, or treatment. Their main relevance is methodological: agreement in effect direction can coexist with different anatomical distributions, indicating that the interpretation of regional findings requires attention to how cortical folding is measured.

Future studies should compare both approaches under harmonized analytical conditions, quantify spatial agreement and effect sizes, and assess findings in independent cohorts. Longitudinal designs could also clarify whether gyrification relates to developmental trajectories or changes in migraine burden. Such evidence is needed to determine whether either measure offers clinically useful information beyond standard clinical assessment. At present, these findings support further methodological investigation rather than the identification of a specific cortical biomarker of pediatric migraine.

Limitations. Several limitations should be considered. This descriptive comparison of previously generated outputs does not establish whether differences between findings arise from the gyrification measures themselves. Spatial overlap and effect sizes were not compared quantitatively, and significance with one measure alone does not demonstrate a significant difference between methods. Sex-related findings cannot be considered migraine-specific because a diagnosis-by-sex interaction was not tested. The cross-sectional design, categorical grouping of age and migraine frequency, and small or imbalanced subgroups may have limited sensitivity. Finally, the absence of independent validation and individual-level performance assessment precludes conclusions about clinical utility.

Conclusions

Conventional FreeSurfer-derived and shape-adaptive Lyu measures identified lower local gyrification in patients than in healthy controls and in female than in male patients, but with different anatomical and hemispheric distributions. Sex-related differences among controls were significant only with the conventional measure. Neither measure identified significant differences related to age, MMDs, photophobia and/or phonophobia, or nausea and/or vomiting. Agreement in effect direction does not establish spatial concordance or the superiority of either approach. These descriptive findings do not establish a specific cortical signature or a clinically useful biomarker of pediatric migraine. Harmonized comparisons, quantitative assessment of agreement, and independent validation are needed to clarify their methodological and potential clinical relevance.

Materials and Methods

Study design. This study was a retrospective methodological reappraisal of local gyrification outputs generated during our earlier regional morphometry project. (10) The study cohort comprised 72 patients with migraine without aura and 82 healthy controls. Both conventional FreeSurfer-derived and shape-adaptive Lyu gyrification measures were calculated in the same individuals, and group comparisons for both measures were analyzed using the PALM. The reappraisal addressed three sets of comparisons: patients *vs.* healthy controls; sex and age subgroups within patients and within controls; and migraine frequency and symptom-defined subgroups within patients. The comparison between gyrification measures was descriptive and focused on whether differences were detected, their direction, and their anatomical distribution. The study workflow is summarized in **Figure 3**.

Medical records were reviewed by an experienced neurologist. Exclusion criteria included abnormal neurological examination, migraine attack during MRI acquisition, ongoing preventive treatment, use of acute migraine medication within 24 hours before MRI, catamenial migraine, sleep disorders, major systemic or psychiatric comorbidities, and maternal disorders during pregnancy. Migraine without aura was confirmed according to the third edition of the *International Classification of Headache Disorders* criteria. (10)

Healthy controls aged 6-18 years had high-quality MRI examinations without morphological or signal abnormalities and underwent neurological assessment to exclude migraine and other neurological disorders. Controls were selected to obtain comparable age and sex distributions at the group level, without individual case-to-control matching. (10) Because participants were retrospectively identified from a hospital imaging archive, selection bias cannot be excluded.

MRI acquisition and cortical reconstruction. All MRI examinations were acquired using the same 3-T Magnetom Skyra scanner (Siemens, Erlangen, Germany) with a 32-channel head coil. The protocol included axial and coronal T2-weighted imaging, axial fluid-attenuated inversion recovery, diffusion-weighted imaging, and a high-resolution sagittal 3D T1-weighted magnetization-prepared rapid acquisition gradient-echo sequence (repetition time = 1570 ms, echo time = 2.67 ms, inversion time = 900 ms, flip angle = 9°, slice thickness = 0.8 mm). (10) Structural data were processed with FreeSurfer 5.3 using the standard recon-all pipeline and visual quality control. (10)

MRI was performed at least 72 hours after complete resolution of the preceding migraine headache and any associated postdromal symptoms. The absence of headache and migraine-related symptoms was also verified during the 72 hours following MRI, supporting an interictal acquisition.

Local gyrification approaches. Local gyrification was calculated

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using two approaches (**Figure 4**). Both quantify cortical folding through the ratio between the area of the folded pial surface and the corresponding area of an enclosing outer surface. The conventional method described by Schaer *et al.* and implemented in FreeSurfer defines circular local regions on the outer surface and identifies their corresponding patches on the pial surface. (9,31) The shape-adaptive method proposed by Lyu *et al.* instead defines a neighborhood whose shape adapts to local cortical geometry, elongating along gyral crowns and sulcal fundi while remaining more uniform over sulcal banks. (14)

Both measures were calculated from the same cortical surfaces reconstructed using the standard FreeSurfer 5.3 pipeline. The conventional measure was obtained using the FreeSurfer implementation, whereas the shape-adaptive measure was obtained by applying the Lyu algorithm to the reconstructed surfaces, as described in our previous study. (10) Thus, the approaches shared the surface reconstruction step but differed in the subsequent calculation of local gyrification. Their different neighborhood definitions may produce differences in the spatial representation of cortical folding, without implying that either approach is universally superior.

Clinical variables and subgroup definitions. Local gyrification was first compared between patients with migraine without aura and healthy controls. This patient-control comparison was also performed separately among participants aged <12 years and those aged ≥12 years. Within the patient group, females were compared with males, and participants aged <12 years were compared with those aged ≥12 years. The same within-group comparisons were performed in healthy controls. Additional comparisons were restricted to patients and addressed migraine frequency (<8 *vs.* ≥8 MMDs), the presence *vs.* absence of photophobia or phonophobia, and the presence *vs.* absence of nausea and/or vomiting. Both gyrification measures were used for all comparisons.

The age threshold of 12 years was used to distinguish younger children from participants in early adolescence, a period associated with changes in migraine epidemiology and the emergence of female predominance. (10) Chronological age was used as a practical grouping variable rather than a direct measure of pubertal maturation.

The threshold of 8 MMDs distinguished lower from higher migraine frequency within this episodic migraine cohort, consistent with some clinical definitions of high-frequency episodic migraine. (15) Symptom-defined comparisons addressed sensory symptoms, represented by photophobia and/or phonophobia, and gastrointestinal symptoms, represented by nausea and/or vomiting. For each symptom pair, patients with either or both symptoms were compared with those with neither.

Statistical inference and interpretation of archived outputs. Vertex-wise group comparisons for both gyrification measures were performed using non-parametric permutation testing implemented in PALM. Group differences were assessed using *t*-statistics with 1,000 permutations per test.

TFCE was applied to enhance spatially coherent effects without specifying an initial cluster-forming threshold. Statistical significance was defined as FWE-corrected p<0.05. (10)

For each patient-control or subgroup comparison, the outputs of the two gyrification measures were reviewed descriptive-

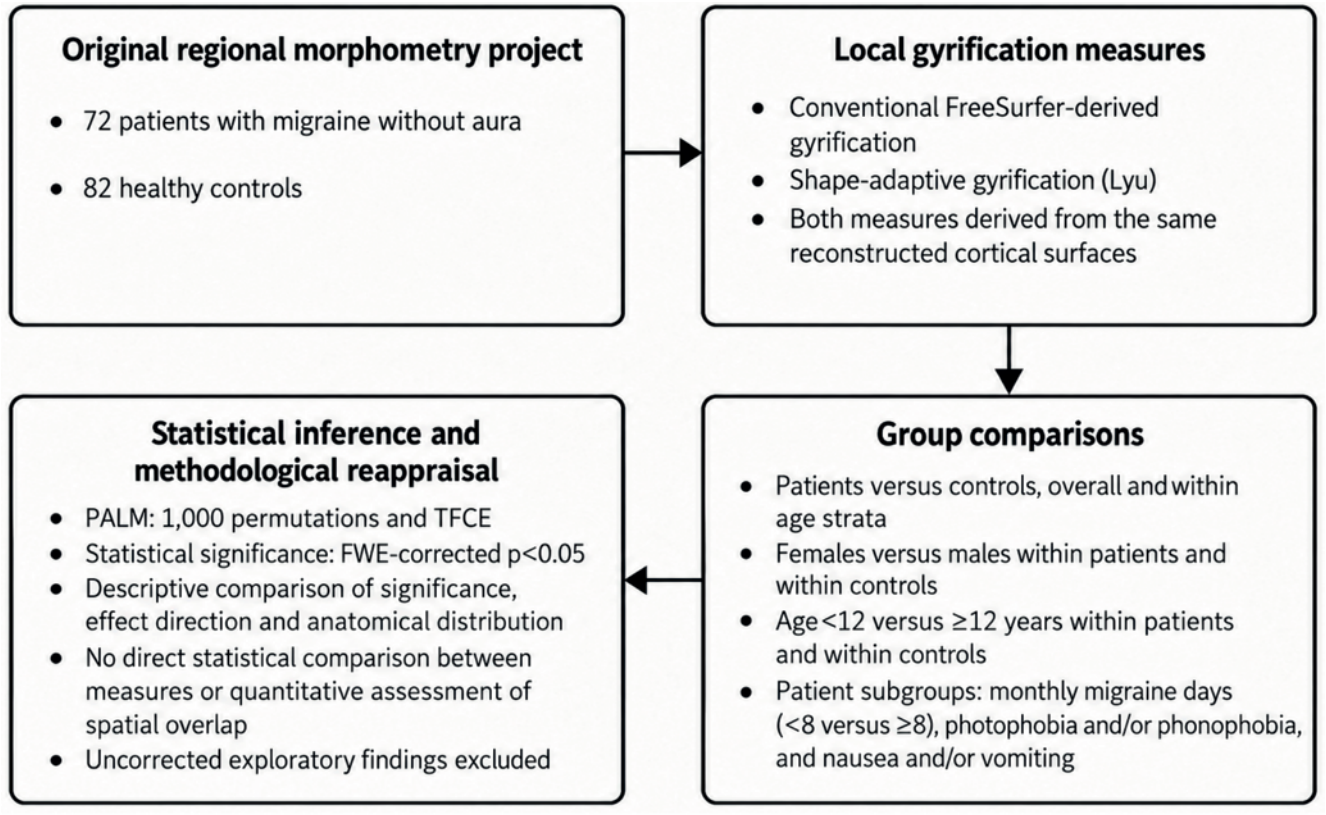


Figure 3. Study workflow. Previously generated local gyrification outputs from 72 patients with migraine without aura and 82 healthy controls were reviewed. Conventional FreeSurfer-derived and shape-adaptive Lyu measures were calculated from the same reconstructed cortical surfaces. Patient-control and subgroup comparisons were assessed using PALM with 1,000 permutations and TFCE, with statistical significance defined as FWE-corrected p<0.05. Findings were compared descriptively across measures according to statistical significance, effect direction, and anatomical distribution.

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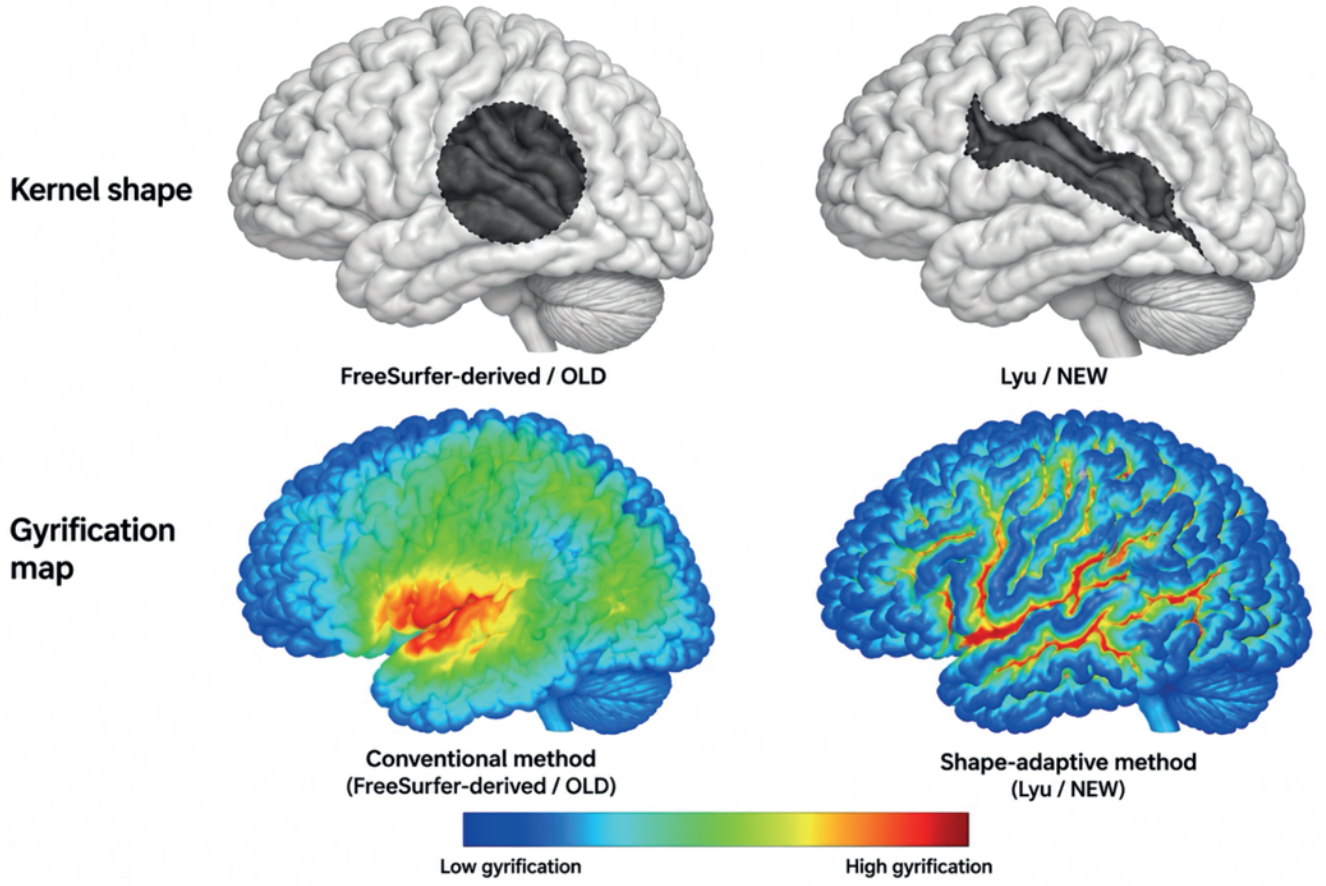


Figure 4. Conventional *vs.* shape-adaptive local gyrification approaches. The upper panels illustrate the different geometrical definitions of the local neighborhood used to quantify cortical folding. The conventional FreeSurfer-derived approach uses a geometrically predefined local neighborhood, whereas the shape-adaptive method proposed by Lyu et al. adapts the kernel to the individual geometry of gyral crowns and sulcal fundi. Both approaches rely on FreeSurfer-reconstructed cortical surfaces. The lower panels schematically illustrate how these different geometrical definitions may generate different spatial representations of local gyrification and do not represent empirical data from the present study. Exact spatial correspondence between methods is therefore not expected.

ly. The reappraisal considered the presence of significant findings, their direction, and their anatomical distribution. Agreement in direction was distinguished from correspondence in anatomical location. No formal statistical comparison between the two measures or quantitative assessment of spatial overlap was performed. Only results surviving correction for multiple comparisons were considered statistically significant. Uncorrected exploratory findings were not included.

No new individual-level MRI preprocessing, vertex-wise statistical testing, imputation, or sensitivity analyses were performed for the present study.

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Conflict of interest: Laura Papetti reports personal and institutional honoraria from Teva, Lilly, Lundbeck, Pfizer, AbbVie, and Epitech, and editorial roles with *The Journal of Headache and Pain*, *Children*, *Confinia Cephalalgica*, and *Frontiers in Neurology*; Massimiliano Valeriani reports personal fees from Ipsen for advisory board participation, lecture honoraria from Teva, and remuneration as Editor-in-Chief of *Pain Research and Management*; Alessia Guarnera reports travel and meeting support from the Radiological Society of North America (RSNA), society committee roles with RSNA, the European Society of Medical Imaging Informatics, and the European Society of Paediatric Radiology, and editorial roles with *Radiology*, *Pediatric Radiology*, *European Journal of Radiology*, *European Journal of Radiology: Artificial Intelligence*, *Journal of Medical Imaging and Interventional Radiology*, and *Spine and Neurology*. The remaining authors declare no conflict of interest.

Ethics approval and consent to participate: the study was conducted in accordance with the ethical standards of the Institutional Research Committee and with the Declaration of Helsinki and its subsequent amendments. Written informed consent was obtained from the patients or their parents/legal guardians, as appropriate, prior to MRI examination.

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