

Aspm specifically maintains symmetric proliferative divisions of neuroepithelial cells

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The ASPM (abnormal spindle-like microcephaly-associated) protein has previously been implicated in the determination of human cerebral cortical size, but the cell biological basis of this regulation has not been studied. Here we investigate the role of *Aspm* in mouse embryonic neuroepithelial (NE) cells, the primary stem and progenitor cells of the mammalian brain. *Aspm* was found to be concentrated at mitotic spindle poles of NE cells and to be down-regulated with their switch from proliferative to neurogenic divisions. Upon RNA interference in telencephalic NE cells, *Aspm* mRNA is reduced, mitotic spindle poles lack *Aspm* protein, and the cleavage plane of NE cells is less frequently oriented perpendicular to the ventricular surface of the neuroepithelium. The alteration in the cleavage plane orientation of NE cells increases the probability that these highly polarized cells undergo asymmetric division, i.e., that apical plasma membrane is inherited by only one of the daughter cells. Concomitant with the resulting increase in adventricular cells in the ventricular zone, a larger proportion of NE cell progeny is found in the neuronal layer, implying a reduction in the number of NE progenitor cells upon *Aspm* knock-down relative to control. Our results demonstrate that *Aspm* is crucial for maintaining a cleavage plane orientation that allows symmetric, proliferative divisions of NE cells during brain development. These data provide a cell biological explanation of the primary microcephaly observed in humans with mutations in *ASPM*, which also has implications for the evolution of mammalian brains.

asymmetric division | brain size evolution | cleavage plane | neurogenesis

The size of the mammalian neocortex is thought to be principally determined by the number of radial units generated during development (1). This lateral expansion largely reflects the number of proliferative divisions of progenitor cells (one progenitor→two progenitors). The primary progenitor cells of the central nervous system are the neuroepithelial (NE) cells, which characteristically exhibit apical–basal polarity (2). A key feature of proliferative divisions of NE cells and of the radial glial cells they transform into (3) is that cleavage occurs along their apical–basal axis, i.e., perpendicular to the ventricular surface of the neuroepithelium, which ensures the symmetric distribution of polarized cell fate determinants to the daughter cells (2, 4, 5). The switch of NE and radial glial cells from symmetric, proliferative divisions to asymmetric, neurogenic divisions (one progenitor→one progenitor plus one neuron/neuronal precursor), which limits the lateral expansion of the neocortex, is accompanied by a deviation of the cleavage plane from the apical–basal orientation (4). This deviation often is only relatively small but nonetheless results in the apical plasma membrane of NE cells being bypassed (rather than bisected) by the cleavage furrow and, hence, being inherited by only one of the daughter cells (5, 6).

NE and radial glial cells are characterized by a highly elongated shape. Consequently, given that junctional complexes at the apical-most end of the lateral plasma membrane separate the apical and basolateral surface domains of these polarized cells, the apical domain constitutes only a minute (1–2%) fraction of

their entire cell surface (5, 7), which, in turn, implies that when these cells undergo symmetric, proliferative divisions, the mitotic spindle must be oriented exactly perpendicular to their apical–basal axis to ensure that the cleavage furrow will bisect (rather than bypass) the apical domain. It follows that NE and radial glial cells, in particular, should express proteins that maintain this spindle orientation and do so especially during symmetric, proliferative divisions and, given that the cleavage furrow ingresses in the basal-to-apical direction (5), until the very end of M phase.

The *Aspm* (abnormal spindle-like microcephaly-associated) protein (8) is an interesting candidate for such a role for several reasons. First, the *Drosophila* homologue of *Aspm*, *Asp*, exerts a critical role at spindle poles during mitosis (9). Specifically, *Asp* is thought to focus microtubules, including those of the central spindle (10), a key structure for the positioning of the cleavage furrow (11). Similar to *Asp*, *ASPM* in nonneural human cells has recently been shown to localize to spindle poles (12–14), suggesting that it may be involved in some aspect of mitotic spindle function in mammalian cells.

Second, mutations in *ASPM* are the most common cause of primary microcephaly in humans (8, 15), indicating a direct role for this protein in regulating cerebral cortical size. Interestingly, the macroscopic structure of the cerebral cortex in these humans (8) suggests a reduction in the generation of radial units during cortical development, which raises the possibility that *ASPM* is required for the maintenance of symmetric, proliferative divisions of NE cells. Consistent with a role of *Aspm* in the lateral expansion of the neocortex, the primate and human lineages show strong positive selection for evolutionary change in the *Aspm* protein (16, 17).

Together, these data suggest that *Aspm* may regulate cerebral cortical size by controlling an aspect of mitotic spindle function that is crucial for maintaining symmetric, proliferative divisions of the highly elongated, polarized NE cells (2), thereby allowing the lateral expansion of the neocortex. In the present study, we have investigated a possible role of *Aspm* in regulating cleavage plane orientation and symmetric, proliferative divisions versus asymmetric, neurogenic divisions of NE cells in the mouse embryonic telencephalon.

Results and Discussion

Down-Regulation of Spindle Pole-Associated *Aspm* in NE Cells Undergoing Neurogenic Divisions. *In situ* hybridization (Fig. 5, which is published as supporting information on the PNAS web site) confirmed previous observations (8, 18) that *Aspm* mRNA is expressed in the ventricular zone (VZ) of the murine embryonic

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Abbreviations: NE, neuroepithelial; VZ, ventricular zone; RNAi, RNA interference; esiRNA, endoribonuclease-prepared, short interfering RNA; En, embryonic day *n*.

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forebrain. Interestingly, *Aspm* expression in NE cells was highest when these cells underwent proliferative (rather than neurogenic) divisions and exhibited a highly (rather than only moderately) elongated shape. Specifically, *Aspm* expression (*i*) was still comparatively rare at early developmental stages [embryonic day (E)8.5], when NE cells are not yet highly elongated (7); (*ii*) was detected in most, if not all, VZ cells around the onset of neurogenesis (E9.5–E11.5), when symmetric, proliferative divisions of NE cells prevail (19); and (*iii*) declined progressively at later stages of neurogenesis (E13.5–E17.5), when an increasing proportion of VZ cells have switched to neurogenic divisions (19). Given these observations, we decided to explore the possibility that *Aspm* may function specifically in the proliferative divisions of NE cells.

To this end, we first determined the subcellular localization of *Aspm* in NE cells. Immunostaining of mitotic NE cells in the E12.5 mouse telencephalon using an affinity-purified antibody raised against recombinant mouse *Aspm*_{150–263} showed that *Aspm* was concentrated at the poles of the mitotic spindle (Fig. 1A; see also Fig. 6, which is published as supporting information on the PNAS web site). Specifically, *Aspm* immunoreactivity was clustered in the immediate vicinity of, but did not overlap with, the γ -tubulin staining of centrosomes. Association of *Aspm* with the spindle poles was observed during all phases of mitosis, with an apparent decrease in the intensity of immunostaining in telophase (Figs. 1A and 6). However, *Aspm* did not appear to be associated with centrosomes during interphase (Fig. 2B, arrows). The association of *Aspm* with the spindle poles of NE cells is consistent with previous observations on the subcellular localization of *Aspm* in mitotic *Drosophila* neuroblasts (9) and of *ASPM* in mitotic nonneural human cells in culture (12–14).

If *Aspm* has a critical function in maintaining spindle orientation during symmetric, proliferative NE cell divisions, one might expect that it is more highly expressed in proliferating than neuron-generating NE cells. To address this issue, we made use of *Tis21*-GFP knockin mouse embryos (19) in which GFP in the developing central nervous system is selectively expressed in progenitors undergoing neurogenic divisions but not in progenitors undergoing proliferative divisions. Indeed, comparative analysis of the telencephalon of E14.5 *Tis21*-GFP knockin mice revealed that *Tis21*-GFP-negative NE cells tended to exhibit more intense *Aspm* immunostaining at spindle poles than did *Tis21*-GFP-positive NE cells (Fig. 1C), as exemplified for three neighboring metaphase NE cells in Fig. 1B. In no case did we observe more intense *Aspm* staining in *Tis21*-GFP-positive than in *Tis21*-GFP-negative cells. These data indicate that *Aspm* is down-regulated in NE cells concomitant with their switch from proliferative to neurogenic divisions.

Knockdown of *Aspm* Perturbs Vertical Cleavage Plane Orientation.

Given these observations, we explored whether *Aspm* contributes to maintaining the mitotic spindle positioned perpendicular to the apical–basal axis of NE cells, thus ensuring bisection of their apical plasma membrane and, hence, their symmetric division (5). *Aspm* was knocked down by RNA interference (RNAi) elicited by electroporation of endoribonuclease-prepared, short interfering RNAs (esiRNAs; a mixture of short interfering RNAs) along with a monomeric red fluorescent protein (mRFP) plasmid into one telencephalic hemisphere of E10.5 or E12.5 mice followed by development for 24 h in whole-embryo culture or *in utero*, respectively (20, 21). This protocol indeed resulted in a reduction in *Aspm* mRNA levels (Fig. 2A) and the loss of spindle pole-associated *Aspm* protein (Fig. 2B, arrowheads). *Aspm* knockdown did not perturb the localization of centrosomes in NE cells in interphase, which remained associated with the apical cell cortex (Fig. 2C, arrowheads), consistent with previous observations (22).

However, *Aspm* knockdown had severe effects on centrosome

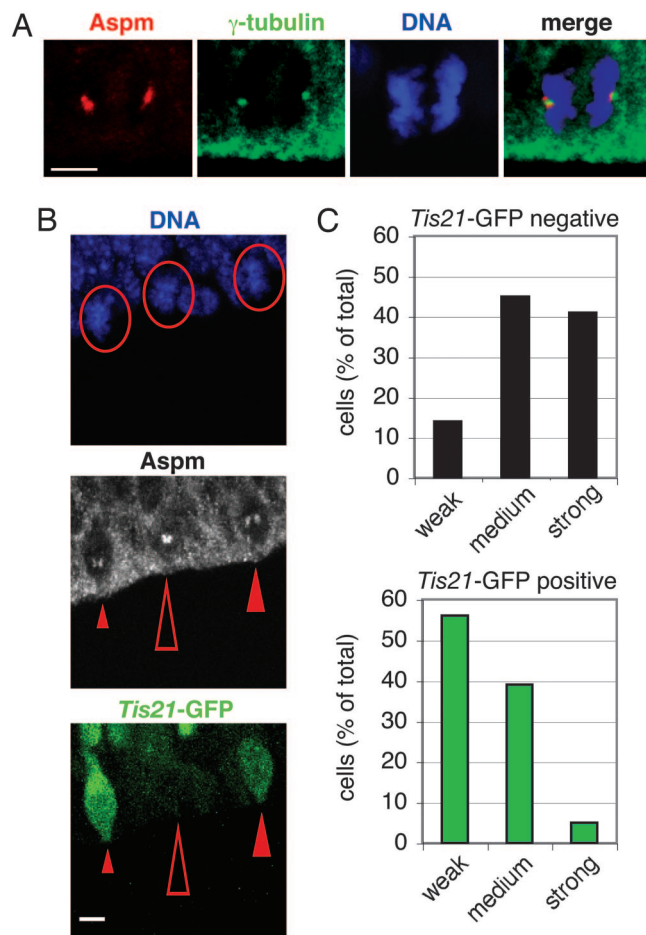
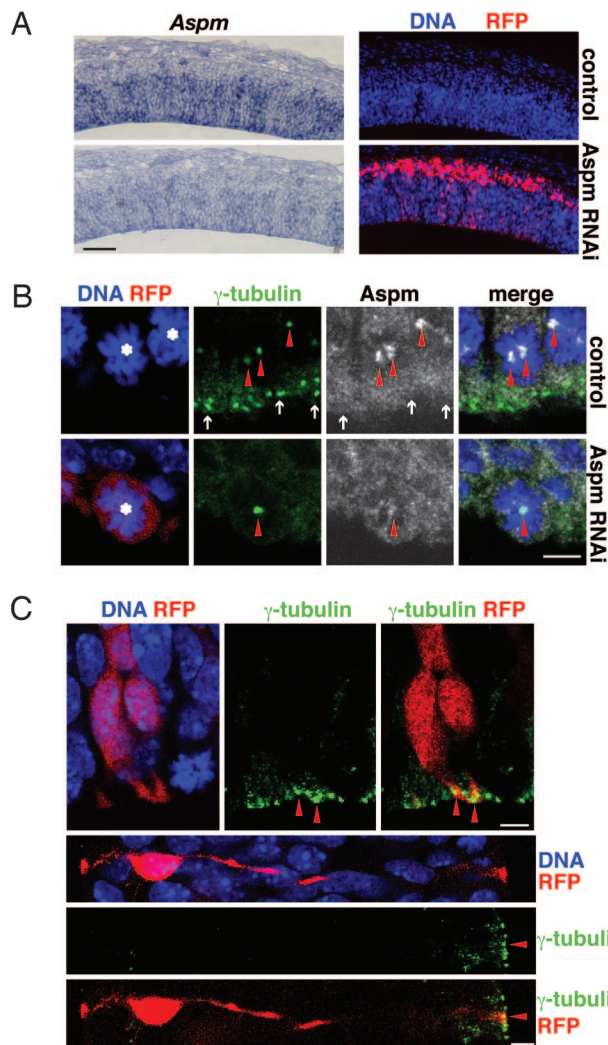


Fig. 1. *Aspm* is concentrated at the spindle poles during mitosis and is down-regulated in NE cells undergoing neurogenic divisions. (A) The dorsal telencephalon of E12.5 *Tis21*-GFP knockin mice was stained with DAPI (DNA, blue) to reveal NE cells in anaphase and immunostained for *Aspm* (red) and γ -tubulin (green). All cells analyzed were *Tis21*-GFP-negative (data not shown). Note the concentration of *Aspm* in the immediate vicinity of the γ -tubulin-stained centrosomes. (Scale bar, 5 μ m.) (B) Comparison of *Aspm* immunoreactivity at spindle poles in metaphase *Tis21*-GFP-negative NE cells (proliferative divisions, open arrowheads) versus *Tis21*-GFP-positive NE cells (neurogenic divisions, filled arrowheads) in the dorsal telencephalon of an E14.5 *Tis21*-GFP knockin mouse. (Top) DNA staining using DAPI (blue); circles indicate the three metaphase cells analyzed. (Middle) *Aspm* immunoreactivity (white); the small, medium, and large arrowheads indicate weak, medium, and strong *Aspm* immunoreactivity at spindle poles, respectively. (Bottom) *Tis21*-GFP fluorescence (green). (Scale bar, 5 μ m.) (A and B) The apical surface of the VZ is down. (C) Quantification in the dorsal telencephalon of E14.5 *Tis21*-GFP knockin mice of prophase or metaphase *Tis21*-GFP-negative (black bars, 22 cells) and *Tis21*-GFP-positive (green bars, 18 cells) NE cells showing weak, medium, or strong *Aspm* immunoreactivity at spindle poles, expressed as a percentage of total (weak plus medium plus strong). Data are from 19 cryosections that originated from at least four brains.

localization in M-phase NE cells. Centrosomes were frequently seen detached from the sister chromatids (Fig. 3A Lower, arrowheads). This phenotype was particularly evident in telophase cells and was not observed before anaphase, suggesting that centrosome detachment due to loss of *Aspm* may occur during sister chromatid separation.

A related aspect of this phenotype was a significant alteration in the orientation of the cleavage plane of *Tis21*-GFP-negative NE cells, which normally is vertical, i.e., perpendicular or nearly perpendicular to the ventricular surface of the neuroepithelium (compare with Fig. 3A Upper, dashed lines) (5). Deduction of the



cleavage plane from the orientation of the sister chromatids of NE cells in anaphase/early telophase (5) revealed that, in agreement with these previous observations, nearly all mitotic

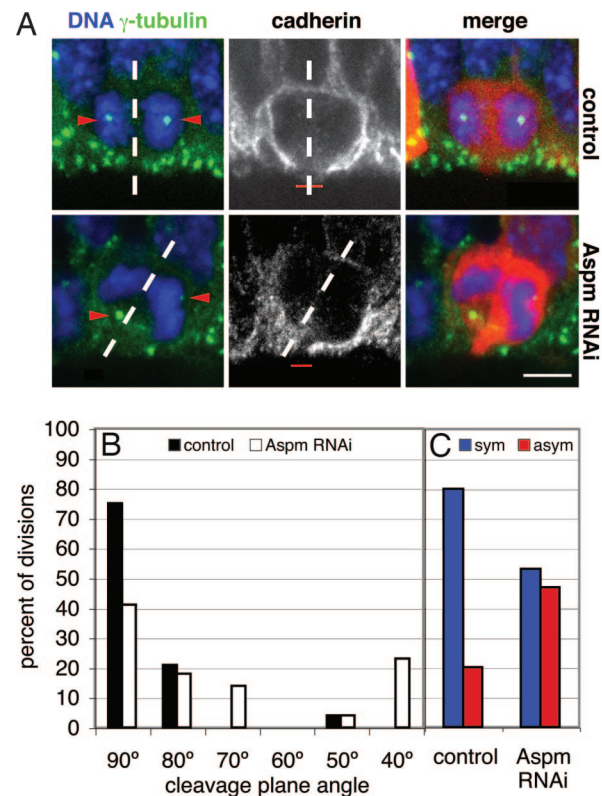


Fig. 3. Knockdown of Aspm alters the cleavage plane of NE cells, resulting in their asymmetric division. (A) Cleavage plane and cadherin hole analysis. Mouse E12.5 dorsal telencephalon was either electroporated with mRFP plasmid only (*Upper*) or coelectroporated with Aspm esiRNAs and mRFP plasmid (*Lower*), followed by 24 h of *in utero* development, and cryosections were analyzed for NE cells in anaphase or telophase by DNA staining with DAPI (blue), RFP fluorescence (red), and γ -tubulin (green) and cadherin (white) immunofluorescence. The cleavage plane (dashed lines) was deduced from the orientation of the sister chromatids (5, 6). Note the aberrant position of the γ -tubulin-stained centrosomes (arrowheads, stack of optical sections) in the targeted cell and the oblique cleavage plane, which bypasses the cadherin hole (red bar, single optical section), upon Aspm knockdown. The apical surface of the VZ is down. (Scale bar, 5 μ m.) (B and C) Quantification of cleavage plane orientation (B) and cadherin hole distribution (C). Dorsal telencephalon of E10.5 *Tis21*-GFP knockin mice was electroporated with mRFP plasmid only (control) or coelectroporated with mRFP plasmid and Aspm esiRNAs (Aspm RNAi), followed by 24 h of whole-embryo culture. *Tis21*-GFP-negative, mRFP-expressing NE cells in anaphase or telophase were analyzed for cleavage plane orientation and the position of the cadherin hole as in A. (B) Orientation of the cleavage plane relative to the radial, apical–basal axis of the neuroepithelium (defined as 90°), expressed as a percentage of all divisions for the control (black bars; $n = 24$) or Aspm RNAi (white bars; $n = 22$) condition. Groups of cleavage plane angle are $\pm 5^\circ$. (C) Cleavage planes bisecting [symmetric (sym), blue bars] or bypassing [asymmetric (asym), red bars] the cadherin hole, expressed as a percentage of all divisions for the control ($n = 15$) or Aspm RNAi ($n = 15$) condition.

We observed a significant increase in adventricular centrosomes in the VZ of the targeted hemisphere (Fig. 4A, *Aspm* RNAi) compared with the nontargeted hemisphere (Fig. 4A,

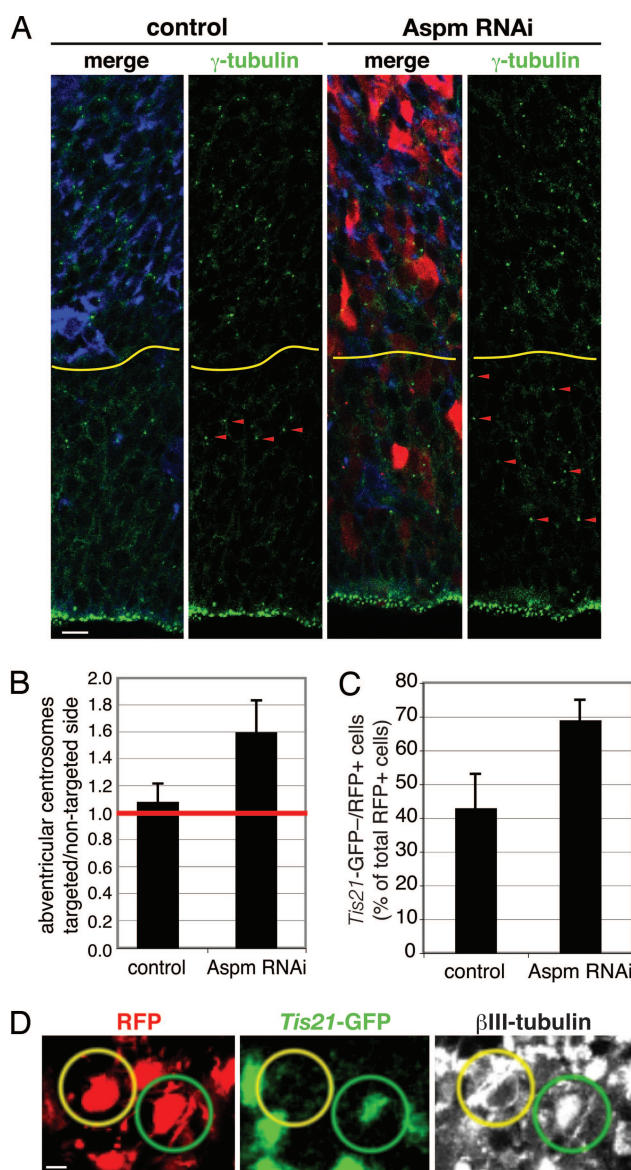


Fig. 4. Knockdown of *Aspm* promotes VZ cells to adopt a non-NE fate and increases the appearance of neuron-like NE cell progeny in the neuronal layer. (A and B) Mouse E12.5 dorsal telencephalon was either coelectroporated with *Aspm* esiRNAs and mRFP plasmid (A and B) or electroporated with mRFP plasmid only (B), followed by 48 h *in utero* development. (A) Cryosections of the nontargeted (control) and targeted (*Aspm* RNAi) hemispheres were analyzed for RFP fluorescence (red) and γ -tubulin (green) and β III-tubulin (blue) immunofluorescence. Note the increase in adventitious centrosomes (arrowheads) upon *Aspm* knockdown. The yellow lines indicate the boundary between the VZ/sub-VZ and the neuronal layers. The apical surface of the VZ is down. (Scale bar, 10 μ m.) (B) Numbers of centrosomes per 10,000 μ m² counted in γ -tubulin-immunostained cryosections are expressed as a ratio of targeted/nontargeted hemispheres for electroporation with mRFP plasmid only (control) and mRFP plasmid plus *Aspm* esiRNAs (*Aspm* RNAi). Data are the mean of five cryosections from three different embryos each; error bars indicate SD. (C and D) Dorsal telencephalon of E10.5 *Tis21*-GFP knockin mice was coelectroporated with *Aspm* esiRNAs and mRFP plasmid (*Aspm* RNAi) or electroporated with mRFP plasmid only (control), followed by 24 h of whole-embryo culture. (C) Cryosections were analyzed for the proportion of RFP-positive cells in the neuronal layer that lacked *Tis21*-GFP fluorescence. Data are the mean of three cryosections from two to three different embryos each (control, 70 cells; *Aspm* RNAi, 74 cells); error bars indicate SD. (D) Representative example of two neighboring RFP-positive cell bodies (red) in the neuronal layer, with one being positive (green circles) and one being negative (yellow circles) for *Tis21*-GFP fluorescence (green) but both exhibiting β III-tubulin immunofluorescence (white). (Scale bar, 5 μ m.)

control) 48 h after initiation of *Aspm* knockdown in E12.5 mice. This increase was 1.6-fold over the abventricular centrosomes observed in the VZ under control conditions (Fig. 4*B*), which is what would be expected, given (i) the efficiency of the targeting of NE cells upon *in utero* electroporation (<50%), (ii) the normal abundance of abventricular centrosomes (compare with Fig. 4*A*, control), (iii) the proportion of NE cells undergoing proliferative divisions at this developmental stage (19), and (iv) the increase in asymmetric NE cell divisions upon *Aspm* knockdown (Fig. 3*C*), among other parameters. The increase in abventricular centrosomes was due to the presence of *Aspm* esiRNAs, because no such increase was observed upon electroporation of the mRFP reporter plasmid alone (Fig. 4*B*, control). Because *Aspm* knockdown did not perturb the apical localization of centrosomes in interphase NE cells (Fig. 2*C*), we conclude that knockdown of *Aspm* causes NE cells to increasingly generate progeny with abventricular centrosomes, i.e., non-NE progeny.

Increased Neuron-Like Fate of NE Cell Progeny After *Aspm* Knockdown. Does the non-NE progeny generated by *Aspm* knockdown exhibit characteristics of neurons? In contrast to the increase in abventricular centrosomes (Fig. 4*A* and *B*), we did not observe an obvious increase, after *Aspm* knockdown, in VZ cells expressing β III-tubulin (data not shown), a marker of young neurons. This finding, however, does not necessarily mean that there is no increase in neuronal progeny upon *Aspm* knockdown. Live imaging results for telencephalic neuroepithelium of transgenic mouse embryos expressing GFP under the control of the β III-tubulin promoter imply that β III-tubulin expression in the majority of cells born at the ventricular surface occurs relatively late (>5 h after birth), that is, when these cells have left the VZ (A. Attardo, W. Haubensak, F. Calegari, and W.B.H., unpublished data). We therefore analyzed the neuronal layer of the targeted hemisphere of *Tis21*-GFP knockin mouse embryos subjected to *Aspm* knockdown at E10.5 followed by 24 h of whole-embryo culture.

Consistent with previous observations (19), in the control condition (electroporation of RFP only), less than half of the young neurons (identified by β III-tubulin immunofluorescence) in the neuronal layer adjacent to the VZ that derived from electroporated NE cells, as indicated by RFP fluorescence, lacked GFP fluorescence (Fig. 4*C*, control). *Aspm* knockdown resulted in a significant increase in the proportion of GFP-negative/RFP-positive cells in the neuronal layer (Fig. 4*C*, *Aspm* RNAi), suggesting an increasing contribution of progeny derived from NE cells lacking *Tis21*-GFP expression. Remarkably, almost all of the GFP-negative/RFP-positive cells in the neuronal layer observed upon *Aspm* knockdown showed β III-tubulin expression, as exemplified in Fig. 4*D*. We conclude that at least some of the non-NE progeny generated by *Aspm* knockdown migrate to the neuronal layer and express neuronal markers.

In the telencephalon, neurons arise from NE and radial glial cells dividing at the ventricular surface and from progenitors dividing basally in the VZ and sub-VZ (19, 29, 30). Given that the centrosomes of the basal progenitors are abventricular, we examined whether the increase in abventricular centrosomes in the VZ upon *Aspm* knockdown reflected an increase in basal progenitors. However, no obvious increase in abventricular mitotic cells was observed upon *Aspm* RNAi (Fig. 7). This lack of increase in basal progenitors in turn suggests that the neuron-like cells observed in the neuronal layer after *Aspm* knockdown (Fig. 4*C* and *D*) were generated directly by NE cells.

Taken together, our observations indicate that *Aspm* knockdown in NE cells increases the probability of their progeny adopting a non-NE fate, including a neuron-like fate (migration to neuronal layers and expression of neuronal markers). We do

not know whether the neuron-like cells observed develop into functional neurons, and we cannot exclude that the progeny generated by the *Aspm*-knocked-down NE cells, including the neuron-like cells, eventually undergo apoptosis. Importantly, whichever fate the progeny ultimately adopt, it is a non-NE fate, which in any case implies a reduction in the NE progenitor pool relative to control.

Conclusion

In conclusion, our results provide a cell biological explanation for the function of *Aspm* in mammalian neocortical development. The need of the highly elongated, polarized NE cells to bisect their small apical membrane for symmetric, proliferative division (5, 7) implies not only that the mitotic spindle has to adopt an axis exactly perpendicular to the NE cell apical-basal axis by the end of metaphase, it also necessitates that this spindle axis is maintained during anaphase and telophase to ensure that the basal-to-apical ingression of the cleavage furrow (5) occurs precisely along the apical-basal NE cell axis. Our observations suggest that *Aspm* exerts a critical role at the spindle poles of NE cells in maintaining spindle position through mitosis and, consequently, in ensuring the precise cleavage plane orientation required for symmetric, proliferative divisions.

Loss of *Aspm* upon knockdown results in a deviation of spindle position and, hence, an alteration in cleavage plane orientation, thereby increasing the probability of asymmetric division of NE cells, with only one daughter cell inheriting apical membrane and adherens junctions and, thus, remaining epithelial. In other words, loss of *Aspm* reduces the expansion of the NE progenitor pool, which would explain why humans with mutations in *ASPM* suffer from primary microcephaly (8). [Similar considerations may hold true for mutations in other genes encoding centrosomal proteins that cause primary microcephaly (12, 31).] The observation that only the brain is affected in these patients (32), despite the expression of *Aspm* in other developing epithelia (13), likely reflects the highly elongated shape of NE cells and their small apical membrane, which make them more vulnerable to any perturbations in spindle position when undergoing symmetric, proliferative divisions (2, 7). A corollary of this is that with the increase in brain size during primate evolution, the further reduction in the apical membrane of NE cells, which predicts the need for even greater accuracy of cleavage plane orientation, offers a potential reason for the positive selection of *ASPM* observed in the primate lineage (16, 17).

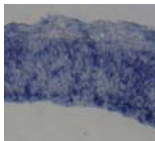
Methods

Animals. All experiments with *Tis21*-GFP knockin mice were performed on heterozygous embryos obtained from crossing homozygous males with C57BL/6J females (19). Wild-type embryos were obtained from Naval Medical Research Institute (NMRI) mice. The vaginal plug was defined as E0.5. BrdU labeling was performed for 30 min as described (33).

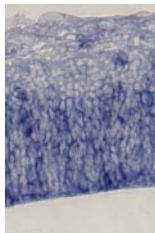
***Aspm* Antibody.** GST-tagged recombinant protein from mouse *Aspm* exon 3 (8), representing amino acids 150–263, was used as an immunogen in rabbits. The resulting antisera were affinity-purified. Antisera and affinity-purified *Aspm* antibodies were tested first in immunoblots of total protein of Cos-7 cells overexpressing a GFP-*Aspm*_{150–263} fusion protein. The specificity of the affinity-purified *Aspm* antibodies was further corroborated in immunoblots of total protein from mouse E12.5–E13.5 heads, in which a band of >300 kDa [and three to four bands with lower molecular weights, presumably representing splice variants (13)] were recognized.



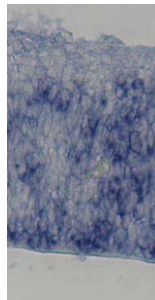
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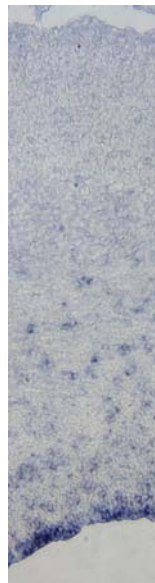
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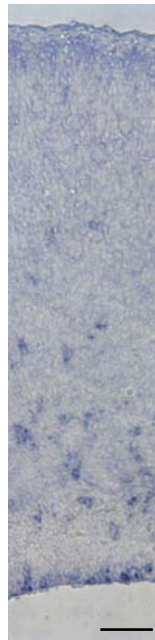
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E13.5



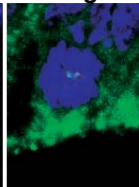
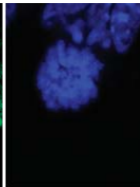
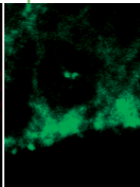
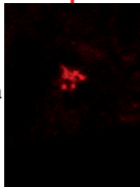
E15.5



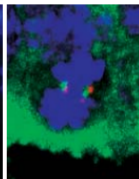
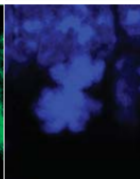
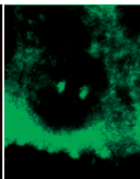
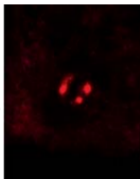
E17.5

Aspm **γ -tubulin****DNA****merge**

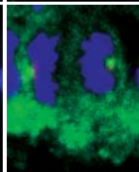
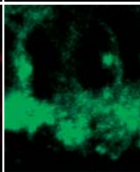
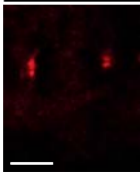
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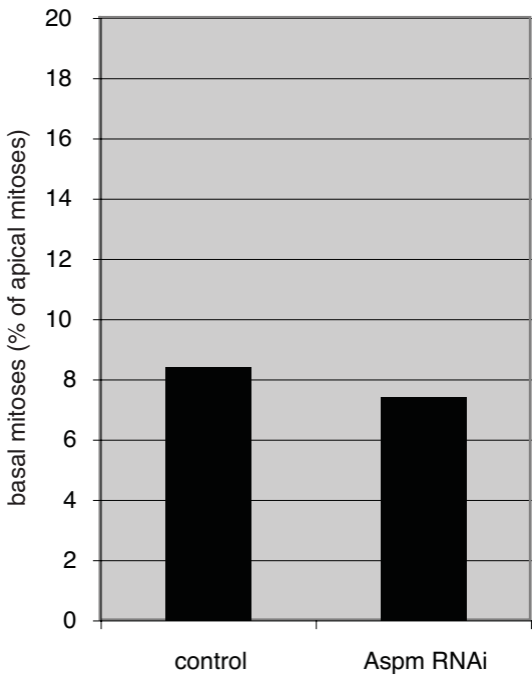


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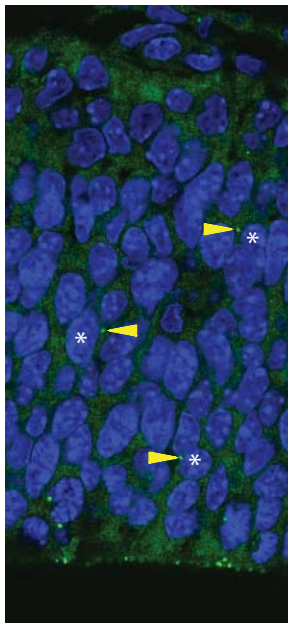


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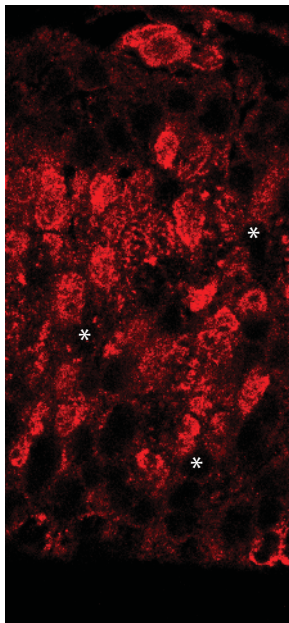




DNA γ -tubulin



BrdU



merge

