MPP3 Is Required for Maintenance of the Apical Junctional Complex, Neuronal Migration, and Stratification in the Developing Cortex

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During mammalian cortical development, division of progenitor cells occurs at the apical ventricular zone. Apical complex proteins and adherens junctions regulate the different modes of division. Here, we have identified the membrane-associated guanylate kinase protein membrane palmitoylated protein 3 (MPP3) as an essential protein for the maintenance of these complexes. MPP3 localizes at the apical membrane in which it shows partial colocalization with adherens junction proteins and apical proteins. We generated Mpp3 conditional knock-out mice and specifically ablated Mpp3 expression in cortical progenitor cells. Conditional deletion of Mpp3 during cortical development resulted in a gradual loss of the apical complex proteins and disrupted adherens junctions. Although there is cellular disorganization in the ventricular zone, gross morphology of the cortex was unaffected during loss of MPP3. However, in the ventricular zone, removal of MPP3 resulted in randomization of spindle orientation and ectopically localized mitotic cells. Loss of MPP3 in the developing cortex resulted in delayed migration of progenitor cells, whereas the rate of cell division and exit from the cell cycle was not affected. This resulted in defects in cortical stratification and ectopically localized layer II–IV pyramidal neurons and interneurons. These data show that MPP3 is required for maintenance of the apical protein complex and adherens junctions and for stratification and proper migration of neurons during the development of the cortex.

Introduction
Mammalian cortical development is a highly regulated process, in which cell division occurs at the apical side in the ventricular zone (Lehtinen and Walsh, 2011). Progenitor cells undergo symmetric division, after which the daughter cells stay as progenitors at the ventricular zone, or asymmetric division, after which one of the daughter cells relocates to the basal surface along radial glia and differentiates into a specific type of neuron (Zhong and Chia, 2008). There is a delicate balance between maintaining the progenitor pool and cell division. Here, we have identified the membrane-associated guanylate kinase protein membrane palmitoylated protein 3 (MPP3) as an essential protein for the maintenance of these complexes. MPP3 localizes at the apical membrane in which it shows partial colocalization with adherens junction proteins and apical proteins. We generated Mpp3 conditional knock-out mice and specifically ablated Mpp3 expression in cortical progenitor cells.

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MPP3 also interacts with the Nectin1 adherens junction protein (Dudak et al., 2011).

Here, we show that MPP3 is expressed during cortical development and partially colocalized with PALS1 and with adherens junction proteins. To further address the role of MPP3 in the developing cortex, we removed MPP3 specifically in the developing cortex. Removal of MPP3 results in a loss of the apical protein complex and a disruption of adherens junctions. Furthermore, we show that, although cell division is not affected, loss of MPP3 results in delayed migration of progenitor cells and ectopically localized late-born neurons in adult cortex. As such, we hypothesize that MPP3 plays an important role as a link between the apical protein complex and adherens junctions in the developing cortex.

Materials and Methods

Generation of Mpp3 conditional knock-out mice. To generate Mpp3 conditional knock-out (cKO) mice, a targeting construct was generated with an flippase recognition target (FRT) flanked Neomycin cassette positioned between exons 6 and 7 of the Mpp3 gene and flanked by 10 and 4 kb 5’ and 3’ homology arms, respectively. The FRT–Neomycin cassette also contained a loxP site, and a loxP site was introduced in the 5’ homology arm 2 kb upstream of the third exon of Mpp3, which is the exon starting the start codon. The targeting vector was linearized with NotI and Nrul and electroporated in 129Ola embryonic day 14 (E14) embryonic stem cells. Neomycin-resistant embryonic stem cells were tested containing the start codon. The targeting vector was linearized with NotI and the brains were removed from the skull and stored at 20°C. After Ki67 labeling, sections were heated in the microwave in 10 mM sodium citrate (Invitrogen) and subsequently transferred onto PVDF membranes. After transfer, membranes were blocked by TBS (50 mM Tris, pH 7.5, 150 mM NaCl) supplemented with 1% BSA and 1% nonfat milk and incubated with primary antibodies (anti-MPP3 CPH8 and anti-actin; Millipore Bioscience Research Reagents) for 1 h in T-TBS (TBS supplemented with 0.05% Tween 20). Blots were washed with T-TBS and incubated in secondary antibodies (streptavidin IRDye conjugated; Rockland Immunocytocemicals) in TBS for 1 h. After washing, bands were visualized using the Odyssey Infrared Imaging system (Li-Cor Biosciences) and quantified by NIH Imagej or Adobe Photoshop 7.0 (Adobe Systems) software.

Protein chemistry. Cortices from embryonic mice were dissected and homogenized in ice-cold lysis buffer containing protease inhibitors. After overnight incubation at 4°C, samples were centrifuged, and protein concentration in the supernatant was measured by Bradford’s assay. Cortical lysate was loaded on a gradient SDS-PAGE gel (NuPAGE gels; Invitrogen). Nuclei were counterstained with TOP-PRO-3 iodine (Invitrogen) at 1 μm. Sections were analyzed using a Carl Zeiss CLSM 510 confocal microscope. Image analysis was performed with Carl Zeiss LSM Image Browser 3.5 and Adobe Photoshop 7.0 (Adobe Systems) software.

BrdU experiments. For BrdU cell labeling experiments, pregnant female mice obtained from timed matings were injected intraperitoneally at E12.5 with 200 μl (1 mg/ml) of BrdU in physiological salt solution, the mice were killed 30 min after cell cycle injection in E13.5 cortex. BrdU+ cells were counted for injections at E16.5, mice were injected intraperitoneally with 200 μl (1 mg/ml) of BrdU, and pups were killed at P7. Tissue was collected as described above, and for immunohistochemistry, 10 μm cryostat sections were treated with 2 x HCl for 30 min at 37°C, after which sections were incubated three times for 5 min in 10 mM sodium citrate, pH 7.5, supplemented with 0.05% Tween 20. Subsequently, immunohistochemistry was performed using anti-BrdU as described above. For Ki67 labeling, sections were treated in the microwave in 10 mM sodium citrate and further treated as described above.

Quantification and data analysis. For determining spindle orientation, the angle of the spindle in pH3-positive (pH3+) mitotic cells was quantified using the apical membrane as the reference line, and spindle orientation was divided in three bins: 0–30° (horizontal), 31–60° (oblique), and 61–90° (vertical), respectively. For quantifying distribution and number of mitotic or BrdU+ cells, pH3+ or BrdU+ labeled cells were manually counted in E12.5 cortex in 100 μm bins. Mitotic or BrdU+ cells within three cell nuclei from the apical membrane were considered mitotic or BrdU+ cells in the ventricular zone in E12.5 cortex, whereas all other cells were quantified as ectopic pH3+ or BrdU+ cells. For determining percentage of cells with after cell cycle in E13.5 cortex, BrdU+ cells were counted in 100 μm bins and divided by the total number of BrdU+ cells. For quantification of ectopic CUX1+ Cal-
MPP3 is required for neuron migration and stratification

Generation of Mpp3 cKO mice
The murine Mpp3 gene has 19 exons with the start codon in the third exon (Lin et al., 1998). To generate Mpp3 cKO mice, loxP sites were positioned around exons 3–6, which includes the start codon in exon 3 (Fig. 2A). After initial PCR screening, candidate embryonic stem cell clones were checked by Southern blotting to verify the proper homologous recombination of the targeting construct (Fig. 2B, C). Blastocyst injections resulted in two male chimeric mice, which gave germ-line transmission of the targeted gene. Genotyping of mutant mice resulted in a PCR product of ~200 bp attributable to the addition of the loxP site (Fig. 2D).

To address the role of MPP3 in cortical neurogenesis, we crossed the Mpp3 cKO mice with Emx1Cre mice, which express Cre recombinase starting at E9.5 in cortical progenitor cells (Guo et al., 2000b; Jin et al., 2000; Gorski et al., 2002). In E12.5 cKO cortex, levels of MPP3 at the apical membrane are reduced compared with control cortex (Fig. 2E, F, K). In E16.5 Mpp3 cKO cortex, there is a more prominent and widespread reduction of MPP3 (Fig. 2G, H, K). Finally, as shown in Figure 1, in E18.5 control cortex, MPP3 levels at the apical membrane are clearly reduced compared with earlier time points (Fig. 2I) and still further decreased in E18.5 cKO cortex (Fig. 2J).

Loss of MPP3 results in cellular disorganization at the ventricular zone
Interestingly, in E12.5 cKO cortex, we observed a mild cellular disorganization at the ventricular zone (Fig. 2F). In E16.5 cortex, there was a more prominent and broad cellular disorganization at the ventricular zone (Figs. 2H, 3A–D). Importantly, at the level of the third ventricle, in which Cre recombinase is not expressed, MPP3 expression and localization and cellular organization was indistinguishable from control (Fig. 3E, F). However, analysis of gross cortical morphology at E16.5 did not show a defect on either cortical thickness or lamination (Fig. 3G, H). Thus, loss of MPP3 in the cortex results in a cellular disorganization in the ventricular zone, but gross cortical morphology and lamination is unaffected.

Loss of apical protein complex precedes the loss of adherens junctions in Mpp3 cKO cortex
Because loss of MPP3 resulted in cellular disorganization, we were interested whether apical proteins and adherens junction proteins still localized properly in the absence of MPP3. Already at E12.5, there was a clear decrease in PALS1 immunostaining intensity in Mpp3 cKO cortex compared with control cortex (Fig. 4A–F). At areas in which MPP3 levels were still comparable with control, also PALS1 was unaffected, suggesting that there is a direct relationship between loss of MPP3 and loss of PALS1 (Fig. 4G). In addition to PALS1, also the localization of the other apical proteins CRB2, MUPP1, and PATJ was impaired in Mpp3 cKO cortex (Fig. 4H–M). Interestingly, PATJ-labeled progenitor cells are clearly disorganized in Mpp3 cKO cortex compared with control, similar to that observed in retina with a disrupted apical protein complex attributable to removal of CRB2 (Fig. 4L, M) (Alves et al., 2013). Thus, loss of MPP3 results in a disruption of
the apical protein complex and a disorganization of progenitor cells in the ventricular zone. Previous research showed that loss of the apical protein complex resulted in disruption of adherens junctions (Kim et al., 2010). Therefore, we next assessed the effect of removal of Mpp3 on adherens junctions. In E12.5 Mpp3 cKO cortex, the level and localization of the adherens junction markers p120 catenin, Nectin1, N-cadherin, and β/H9252 catenin and cellular organization was still essentially unaffected (Fig. 5 A, B, D and data not shown). However, at areas in which there was already loss of adherens junction proteins, we observed cellular disorganization at the ventricular zone (Fig. 5 C, E). Next, we investigated the distribution of adherens junction proteins in E16.5 cortex. At the level of the third ventricle, in which Cre is not expressed, levels and localization of β/H9252 catenin was indistinguishable between control and Mpp3 cKO (Fig. 5 F, G). In contrast, the pattern of β-catenin expression was clearly disrupted in the Mpp3 cKO cortex, with both fewer and mislocalized β-catenin puncta, suggesting a loss and disruption of adherens junctions (Fig. 5 H, I). Transmembrane adherens junction proteins, including Catenins, Cadherins, and Nectins, are required for proper adherens junction integrity. In contrast to control cortex, in which these proteins showed a punctate pattern, in Mpp3 cKO cortex, there is a partial loss and dyslocalization of p120 catenin, N-cadherin, M-cadherin, and Nectin1 (Fig. 5 J–Q). Immunohistochemistry for another apical complex protein, PAR3, showed that removal of MPP3 also resulted in a loss of PAR3 in E16.5 cortex (Fig. 5 R, S). These data suggest that loss of MPP3 first results in loss of the PALS1 apical protein complex at E12.5, followed by a loss of the PAR apical protein complex and disruption of adherens junctions at the apical membrane at E16.5.

Loss of MPP3 affects spindle orientation and results in increased number of basally localized mitotic cells

Integrity of adherens junctions and apical complex proteins is required for proper spindle orientation in apical progenitor cells and is involved in determining the mode of cell division (Siller and Doe, 2009; Morin and Bellaiche, 2011). Because adherens junctions and apical protein complexes are disrupted in cortex lacking MPP3, we investigated the spindle orientation in Mpp3 cKO mice. To this end, we quantified the spindle orientation in apically localized phospho-pH3 + mitotic progenitor cells at the ventricular zone in E12.5 cortex. In control cortex, the majority of pH3 + progenitor cells have either a horizontal (0–30°, 38.3 ±
4.5%) or a vertical (61–90°, 47.3 ± 4.1%) spindle orientation, with only a minority of cells with oblique spindle orientation (31–60°, 14.5 ± 3.6%; Fig. 6A–C,G). In Mpp3 cKO cortex, the percentage of pH3+ progenitor cells with vertical spindle orientation was not different compared with control (control, 47.3 ± 4.1%; cKO, 41.2 ± 1.7%; n = 2–3 embryos per group, 6–9 images per embryo), but in contrast to control cortex, there was a dramatic increase in percentage of cells with an oblique spindle orientation, suggesting a shift from horizontal to oblique spindle orientation (horizontal: control, 38.3 ± 4.5%; cKO, 22.7 ± 2.0%, p < 0.00448; oblique: control, 14.5 ± 3.6%; cKO, 36.2 ± 2.5%, p < 0.000014; n = 2–3 embryos per group, 6–9 images per embryo). It is hypothesized that cells with an oblique spindle orientation give rise to two daughter cells with more basal localization. To further resolve this issue, we determined the distribution and number of pH3+ cells in E12.5 cortex. In control cortex, the majority of mitotic cells were localized at the ventricular zone at the apical membrane, with only few mitotic cells at more basal locations (Fig. 6H). In Mpp3 cKO cortex, several mitotic cells were localized at the ventricular zone, but there were also several mitotic cells with a more basal distribution (Fig. 6J). Quantification of the total number of pH3+ mitotic cells in E12.5 cortex showed an increased number of mitotic cells in cortex lacking MPP3 (control, 4.71 ± 0.17; cKO, 6.20 ± 0.18 mitotic cells/100 μm, p < 0.00001, n = 3 embryos per group, 5–13 images per embryo; Fig. 6J). Remarkably, the number of apically localized mitotic cells was not different between control and cKO (control, 3.83 ± 0.14; cKO, 4.07 ± 0.15 mitotic cells/100 μm; n = 3 embryos per group, 5–13 images per embryo; Fig. 6J). Instead, the increase in the number of basally localized mitotic cells in cortex lacking MPP3 was attributable for the increase in the total number of mitotic cells (control, 0.88 ± 0.08; cKO, 2.13 ± 0.13 mitotic cells/100 μm, p < 0.00001, n = 3 embryos per group, 5–13 images per embryo; Fig. 6J). This suggests that the shift toward more mitotic cells with oblique spindle orientation results in an increased number of basally localized pH3+ cells in cortex lacking MPP3.

Loss of MPP3 does not affect proliferation but does affect migration

To address whether loss of MPP3 affects cell division, we performed BrdU incorporation experiments and colabeling with BrdU and Ki67 to determine the rate of cell division and percentage of cells exiting the cell cycle. BrdU incorporation occurs during the S-phase of the cell cycle, whereas Ki67 is a marker for dividing cells in all phases of the cell cycle. First, we quantified the number of BrdU+ cells after a short 30 min pulse of BrdU in E12.5 cortex. This revealed that the number of BrdU+ cells was not different between control and Mpp3 cKO in E12.5 cortex (control, 71.7 ± 2.2 BrdU+ cells/100 μm cortex; cKO, 70.3 ± 2.1 BrdU+ cells/100 μm cortex, n = 3 embryos per group, 3–4 images per embryo; Fig. 6K,L). In control cortex, the majority of BrdU+ cells were positioned in the subventricular zone, with only few BrdU+ cells outside this zone (Fig. 6K). Strikingly, in Mpp3 cKO cortex, there were BrdU+ cells that were apically localized from the subventricular zone (Fig. 6L). Quantification of the number of BrdU+ cells within three cell nuclei from the apical membrane showed a twofold increase in apically localized BrdU+ cells in Mpp3 cKO cortex, suggesting either affected interkinetic nuclear movement or neuronal migration (control,
Next, we investigated whether loss of MPP3 resulted in a change in cell fate. Immunohistochemistry for Sox2, which marks the progenitor pool of cells, did not reveal a difference between control and Mpp3 cKO cortex (Fig. 7A, B). Additionally, we did not observe a difference in Tbr1+ early-born neurons and Tuj1+ neurons (Fig. 7C–F). Finally, we investigated the distribution of Tbr2+ cells, which are the intermediate progenitor pool of cells. This showed that the distribution and number of Tbr2+ cells was not different between control and Mpp3 cKO cortex (control, 48.9 ± 2.8 Tbr2+ cells/100 μm2; cKO, 45.7 ± 2.4 Tbr2+ cells/100 μm2, n = 2–3 embryos per group, 4–6 images per embryo; Fig. 7G,H).

**Ectopic localization of late-born neurons attributable to a delay in migration in Mpp3 cKO cortex**

Next, we investigated whether loss of MPP3 resulted in a change in cell fate. Immunohistochemistry on P7 cortex for CTIP2 and CUX1, markers for early-born (E12.5–E14.5) layer V–VI and late-born (E14.5–E16.5) layer II–IV neurons, respectively. Although gross distribution of CTIP2 neurons in lower layers was not affected, stratification was affected during loss of MPP3 because we observed some CTIP2 neurons in upper layers (Fig. 8A–D). Analysis of CUX1+ neuron distribution in control cortex showed that the majority of CUX1+ cells were localized in layers II–IV, with only few ectopic cells in deeper cortical layers (Fig. 8E, F). In contrast, although in Mpp3 cKO the majority of CUX1+ cells occupied layer II–IV, an increased number of ectopic CUX1+ cells in layer V–VI were observed (control, 32 ± 7.1 ectopic CUX1+ cells/image; cKO, 71 ± 8.8 ectopic CUX1+ cells/image, p < 0.00227, n = 2–3 mice per group, 2–4 images per mouse; Fig. 8E, F). This suggests that loss of MPP3 results in a delayed migration of late-born neurons. Next we focused on the distribution of inhibitory interneurons, which are early-born neurons generated in the caudal and medial ganglionic eminences. Interneurons migrate toward the ventricular zone in the dorsal telencephalon and from there migrate toward upper cortical layers during late-developmental stages (Nery et al., 2002; Fishell, 2007). Investigating the distribution of Calretinin interneurons showed an increased number of Calretinin+ interneurons in layer VI of Mpp3 cKO cortex (control, 57.4 ± 8.5 Calretinin+ neurons in layer VI/image; cKO, 130.1 ± 13.4 Calretinin+ neurons in layer VI/image, p < 0.00034, n = 3 mice per group, 2–4 images per mouse; Fig. 8G,H). This again suggests a delayed migration of neurons during late developmental stages. To further delineate the delayed migration of neurons during late developmental stages and to exclude a change in cell fate, we performed BrdU injections in E15.5 embryos and checked the distribution of BrdU cells in P7 cortex. Quantifying the distribution of BrdU+ cells in the cortex, subdivided into five bins (Fig. 8I,J), showed that less BrdU+ cells occupied the superficial layers in Mpp3 cKO cortex (Bin1 control, 43.3 ± 6.1%; cKO, 27.8 ± 2.1%; p < 0.00763; Bin2 control, 27 ± 3.1%; cKO, 18.7 ± 2.1%; p < 0.0464; n = 2–3 mice per group, 2–4 images per mouse; Fig. 8I–K) and that more BrdU+ cells occupied deeper layers (Bin4 control, 6.5 ± 2%; cKO, 18.8 ± 2.2%; p < 0.00446, n = 2–3 mice per group, 2–4 images per mouse; Fig. 8I–K).

Finally, we investigated the distribution of CUX1 and Calretinin cells in the developing cortex. CUX1 upper layer neurons are born at approximately E16; therefore, at E16.5, CUX1 neurons start to migrate to layer II–IV. First of all, quantification of the number of CUX1+ cells at E16.5 revealed that no difference was observed between control and cKO (control, 28.4 ± 1.24 CUX1+ cells/100 μm2; cKO, 30.6 ± 1.7 CUX1+ cells/100 μm2, n = 3–4 embryos per group, 7–17 images per embryo; Fig. 8L,M). However, quantification of the percentage of CUX1+ cells in the ventricular and intermediate zone and in the cortical plate showed that, although the percentage of CUX1+ cells in the intermediate zone was not different (control, 44.6 ± 1.3%; cKO, 41.3 ± 1.3%), in Mpp3 cKO cortex, a smaller percentage of CUX1+ cells had reached the cortical plate (control, 22.4 ± 1.2%; cKO, 14 ± 0.9%; p < 0.00017, n = 3–4 embryos per
group, 7–17 images per embryo; Fig. 8L–N). Concomitantly, in Mpp3 cKO cortex, a larger percentage of CUX1+ cells still resided in the ventricular zone (control, 33 ± 1.1%; cKO, 44.7 ± 1.3%, \( p < 0.00001 \), \( n = 3–4 \) embryos per group, 7–17 images per embryo; Fig. 8L–N). Additionally, we also investigated the distribution of Calretinin interneurons in E17.5 cortex. This showed that the total number of Calretinin interneurons was not different between control and Mpp3 cKO (control, 27.5 ± 1.4 Calretinin+ cells/100 μm cortex; cKO, 24.2 ± 1.4 Calretinin+ cells/100 μm cortex, \( n = 2 \) embryos per group, 2–4 images per embryo; Fig. 8O–R). However, like the distribution of CUX1+ cells, in Mpp3 cKO cortex, a smaller percentage of Calretinin+ interneurons occupied the cortical plate (control, 41.2 ± 2.2%; cKO, 23.9 ± 2.4%, \( p < 0.00001 \)) and a larger percentage of interneurons was still in the ventricular zone (control, 30.8 ± 1.7%; cKO, 48.1 ± 2.8%, \( p < 0.00001 \)), whereas the percentage of interneurons in the intermediate zone was not different between control and Mpp3 cKO (control, 28 ± 1.3%; cKO, 28 ± 2.3%, \( n = 2 \) embryos per group, 2–4 images per embryo; Fig. 8O–S). These data suggest that removal of MPP3 in the cortex results in delayed migration of late-born neurons and ectopically localized pyramidal CUX1 neurons and Calretinin interneurons in postnatal mice.

Discussion

In this study, we showed that loss of the MAGUK protein MPP3 in the developing cortex results in a disruption of apical complex proteins and adherens junctions, resulting in cellular disorganization at the ventricular zone. Furthermore, although removal of MPP3 does not affect cell division, it does affect spindle orientation and localization of mitotic cells. Finally, we showed that loss of MPP3 results in ectopic localization of late-born neurons attributable to a delay in migration.

We showed that MPP3 is required for maintenance of PALS1 at the apical membrane. There is a striking difference between the Mpp3 and the Pals1 cKO phenotype in the cortex. Gross morphology of Mpp3 cKO cortex is indistinguishable from control cortex, whereas conditional deletion of Pals1 in the cortex resulted in a virtually absent cortex attributable to premature exit from the cell cycle (Kim et al., 2010). An explanation for this could be that remaining levels of PALS1 are still sufficient to maintain proper cell division. However, one could expect that partial loss of PALS1 would result in an intermediate phenotype. Alternatively, we hypothesize that, apart from its role as being a core component of the apical protein complex, PALS1 has another autonomous function in cell division that is independent from MPP3. Finally, it might be that depletion of PALS1 in the Mpp3 cKO cortex is only
reached after PALS1 has fulfilled its most important role in cell division and maintenance of the pool of progenitor cells.

Like in the Pals1 cKO, there is a disruption of adherens junctions during removal of MPP3 in the cortex. Maintenance of adherens junction integrity is vital for proper cell division and cortical organization. For example, loss of the adherens junction protein N-cadherin resulted in basally localized mitotic cells and disrupted cortical lamination (Kadowaki et al., 2007). Furthermore, loss of Reelin, which regulates the function of Cadherin, results in aberrant neuron migration and cortical lamination (Franco et al., 2011). Additionally, loss of Numb and Numbl, proteins interacting with the Cadherin–Catenin adhesion complex, disrupts adherens junctions and affects progenitor cell polarity in the cortex (Rasin et al., 2007). However, the phenotype observed in the Mpp3 mutant cortex is not as prominent as in the N-cadherin, Reelin, and Numb/Numbl mutant mice.

Figure 8. Delayed migration and ectopic localization of late-born neurons in Mpp3 cKO cortex. A–C, In both control (A) and Mpp3 cKO (C) cortex, CTIP2 neurons are localized in lower layers. However, in Mpp3 cKO cortex, there are some ectopically localized CTIP2 neurons in upper layers (arrowheads in C). D, Removal of MPP3 results in stratification defects with ectopic CUX1 (arrows in D) and CTIP2 (arrowheads in D) neurons. E, Distribution of CUX1⁺ cells in control P7 cortex showed that the majority of CUX1⁺ cells reside in layer II–IV with some ectopic CUX1⁺ cells in layer V–VI. F, Also in Mpp3 cKO cortex, the majority of CUX1⁺ cells occupied layers II–IV, but there is an increase in number of ectopically localized CUX1⁺ cells in deeper layers. G, H, Distribution of Calretinin interneurons in control (G) and Mpp3 cKO (H) cortex shows an increased number of interneurons in layer VI. I, J, BrdU injection at E16.5 and analysis of distribution of BrdU⁺ cells in P7 control (I) and Mpp3 cKO (J) cortex. K, Quantification of the distribution of the BrdU⁺ cells shows that, in Mpp3 cKO cortex, fewer cells occupied superficial layers and there are an increased number of BrdU⁺ cells in deeper layers. L–N, Analyzing the distribution of CUX1⁺ cells between E16.5 control (L) and Mpp3 cKO (M) cortex showed that the total number of CUX1⁺ cells was not different. However, the number of CUX1⁺ cells still residing in the ventricular zone was increased, whereas the number of CUX1⁺ cells occupying the cortical plate was decreased (N). O–S, Distribution of Calretinin⁺ interneurons in E17.5 control (O, P) and Mpp3 cKO (Q, R) cortex. P and R are magnifications of Calretinin interneurons in the ventricular zone from O and Q, respectively. There is no difference in the number of Calretinin⁺ interneurons between control and Mpp3 cKO cortex, but the distribution is altered during removal of Mpp3, with a lower percentage of Calretinin⁺ interneurons in the cortical plate, and an increased percentage in the ventricular zone (S). VZ, Ventricular zone; IZ, intermediate zone; CP, cortical plate. *p < 0.05, **p < 0.001. Scale bars, 50 μm.
ally, the cellular disorganization observed is not as prominent as it would be expected after a complete loss of adherens junctions. Therefore, we conclude the disruption and loss of adherens junctions is only partial in our cKO. Indeed, we showed that, in Mpp3 cKO cortex, there is a partial loss and dyslocalization of adherens junction markers. This might be explained by the fact that there is probably functional redundancy with other MAGUK protein scaffolding adherens junction proteins.

Another complex important for proper development of the cortex is the PAR complex (Costa et al., 2008). Deletion of CDC42, a protein that interacts with the PAR complex, in the cortex results in gradual loss of the PAR complex and adherens junctions, accompanied by an affected interkinetic nuclear migration and a thicker and disorganized cortex (Cappello et al., 2006). Likewise, removal of ASP2P2, which is required for proper localization of PAR3, results in aberrant neural progenitor proliferation and affected interkinetic nuclear migration and lamination (Sottocornola et al., 2010). We showed that removal of MPP3 leads to a loss of PAR3 from the apical membrane. However, this is possibly a secondary effect from the loss of other apical complex proteins, and therefore the observed phenotype in the Mpp3 cKO might be more attributable to a loss of apical proteins and adherens junctions rather than a loss of PAR3, an issue that remains difficult to segregate.

In addition to affected migration, the Mpp3 cKO mutant mice display ectopic CUX1-1 layer II–IV pyramidal neurons in layer V–VI and ectopic interneurons. Interestingly, the delayed migration and ectopic localization of late-born CUX1-1 neurons is strikingly similar to the phenotype observed after removal of CNTNAP2, a protein that interacts with several MPP proteins, including MPP3 (Horresh et al., 2008; Peñagarikano et al., 2011). Additionally, these CNTNAP2 KO mice have a reduced number of interneurons and display autism-related behavior and suffer from epileptic seizures (Peñagarikano et al., 2011). In contrast to the CNTNAP2 KO, the Mpp3 cKO does not have a reduction in the number of interneurons but rather has an altered distribution of interneurons. These interneurons are generated in the ganglionic eminences, after which they migrate toward the dorsal telencephalon in which they migrate to the upper layers of the cortex (Nery et al., 2002; Fishell, 2007). Because Cre recombinase in the Emx1-Cre mice is not expressed in the ganglionic eminences (Gorski et al., 2002; Cappello et al., 2006; Liang et al., 2012), generation or initial migration of interneurons is likely not affected, but the final migration from the subventricular zone toward superficial layers might be. Additionally, it cannot be excluded that the affected distribution of interneurons in Mpp3 cKO cortex is a secondary effect attributable to the ectopic CUX1-1 pyramidal neurons in layers V–VI. This delayed migration in Mpp3 cKO cortex could be attributable to affected radial glia-mediated migration of progenitor cells and neurons. Indeed, we showed that not only neuronal migration but also migration of progenitor cells was affected. Mutant mice, such as MARCKS and PTB that show a gradual loss of adherens junctions in the cortex (Weimer et al., 2009; Shibasaki et al., 2012), also have affected migration of neural progenitor cells, suggesting that the disruption of adherens junctions in Mpp3 cKO cortex leads to this aberrant migration.

Importantly, aberrant migration or connectivity of interneurons is associated with a number of neurodevelopmental disorders, such as autism, schizophrenia, and mental retardation (Levitt, 2005; Di Cristo, 2007; Rossignol, 2011). Although we found that the gross morphology of Mpp3 cKO cortex was unaffected, there is a clear stratification defect in Mpp3 cKO cortex and ectopically localized pyramidal neurons and interneurons. Therefore, it is tempting to speculate that MPP3 is a new candidate gene for neurodevelopmental disorders.

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