The Caspase-Related Protease SeparaSe (EXTRA SPINDLE POLES) Regulates Cell Polarity and Cytokinesis in Arabidopsis

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INTRODUCTION

Asymmetric distribution of cellular components defines cell polarity, a fundamental property of all organisms, indispensable for their ability to grow and reproduce (Drubin and Nelson, 1996; Dhonukshe et al., 2008; Asnacios and Hamant, 2012). Due to the sessile nature of plants, their response to developmental and environmental cues requires high plasticity of morphogenetic processes. Furthermore, rigid cell walls limit the range of plant cell responses to internal and external signals involved in the regulation of division plane orientation and the direction of cell expansion. Both cell division and cell expansion are regulated by the phytohormone auxin (Woodward and Bartel, 2005). The physiological activity of auxin is translated through the gradients of its distribution across plant tissues and organs. These gradients are established and maintained by membrane influx and efflux carriers, which are responsible for cell-to-cell auxin transport (Petrásek and Friml, 2009). The direction of gradients is determined by the distribution of the auxin carriers to the sides of the cell, and the pattern of localization asymmetry of these carriers serves as a marker of cell polarity.

The PIN-FORMED (PIN) family of plasma membrane proteins is the most well-studied auxin efflux carriers. PIN proteins are typically asymmetrically organized on the plasma membranes and are more abundant on either the shootward or rootward sides of the cell. Mutations in PINs result in perturbation of the auxin gradients and lead to aberrant development (Dhonukshe et al., 2008; Smith, 2008; Korbei and Luschnig, 2011). The correct distribution of PINs in plant cells relies on protein trafficking pathways throughout the endomembrane system (Boutté et al., 2007; Grunewald and Friml, 2010). During cytokinesis, PINs are secreted to all sides of the cells, resulting in initially apolar localization (Dhonukshe et al., 2008). Thereafter, asymmetric recycling of PINs between shootward or rootward plasma membrane and endosomes leads to the establishment of polarity. Shootward and rootward PIN targeting is regulated by different mechanisms (Kleine-Vehn et al., 2006). The rootward PIN delivery is ARF GEF (for exchange factor of ADP ribosylation factor GTPases) GNM-dependent and sensitive to microtubule depolymerization drug oryzalin (Michniewicz et al., 2007; Kleine-Vehn et al., 2008a, 2008b, 2009; Rahman et al., 2010), whereas...
the shootward delivery utilizes an ARF-GEF GNOM- and microtubule-independent pathway (Feraru and Friml, 2008; Kleine-Vehn et al., 2008a). Besides the involvement of exocytic pathways, clathrin-mediated endocytosis plays an essential role in the recycling of PIN proteins during establishment and maintenance of cell polarity (Dhonukshe et al., 2007; Feraru et al., 2012).

Polar localization of PINs is a dynamic process governed by developmental and environmental cues, including cell differentiation and gravitropic stimulation. The changes in PIN localization depend on the modulation of overall balance between endo- and exocytosis, as well as the changes of spatial distribution of endo- and exocytic activities. Vesicle trafficking is tightly linked to the dynamics of the cytoskeleton. Apart from the aforementioned role of microtubules in the rootward targeting of PIN2 (Kleine-Vehn et al., 2008a), polar localization and dynamics of PIN1, PIN2, and PIN3 depend on the dynamics of the actin filament (Kleine-Vehn et al., 2008a). During cytokinesis, microtubules are thought to direct the vesicles toward the newly synthesized cell plate (Van Damme and Geelen, 2008); hence, PIN delivery to and cycling at the newly produced cell edges must be determined by the microtubule organization and dynamics. This implies the existence of a link between the cytoskeleton, vesicle trafficking, and PINs localization during both mitosis and interphase. The molecular mechanisms underlying this link remain largely elusive.

Analysis of Arabidopsis thaliana mutants compromised in vesicular trafficking helped to unravel the molecular links between cell polarity and vesicular trafficking (Xu and Scheres, 2005; Jaillais et al., 2007; Nakamura et al., 2012). radially swollen4 (rsw4) is a temperature-sensitive point mutation of the EXTRA SPINDLE POLE (ESP) gene encoding the caspase-related protease separase (Wu et al., 2010). This mutation results in the production of an altered ESP protein with a single amino acid substitution (Ala603 to Val603). Knockout (or constant knockdown) of ESP is embryo-lethal due to the failure of chromosome disjunction (Liu and Makaroff, 2006), consistent with the evolutionarily conserved role of ESP in daughter chromatid separation (Ciosk et al., 1998; Hauf et al., 2001; Moschou and Bozhkov, 2012). In addition to this canonical function, the defects in anisotropic (i.e., directionally dependent) cell expansion observed in rsw4 (Wu et al., 2010) implicate ESP in the regulation of cell polarity (Yang et al., 2011). This duality of plant ESP function provides an interesting paradigm to study the role of a protease in the spatiotemporal relationship between karyokinesis and establishment of cell polarity.

Here, we used the weak point mutant allele of ESP (i.e., rsw4) and inducible ESP RNA interference (RNAi) lines to reveal the function of plant ESP in the determination of cell polarity, which would not have been possible if we examined null alleles or constitutive RNAi lines. This phenotypic analysis coupled with live-cell imaging and immunofluorescence microscopy demonstrates that ESP plays an important role in linking membrane protein trafficking with the cytoskeleton and is essential for the asymmetric distribution of PIN2 protein and cytokinesis.

RESULTS

ESP Deficiency Leads to Perturbed Auxin Gradient in the Root Tip

The apparent isotropic expansion of root cells in a temperature-sensitive mutant allele of ESP, rsw4 (Wu et al., 2010), implicates ESP in the regulation of cell polarity during postembryonic development. Since the establishment of polarity in plants is governed by directional flow and uneven distribution of auxin, we compared the patterns of auxin response in the root tips of rsw4 and wild-type plants using the synthetic auxin activity reporter DR5 promoter (proDR5), which is transcriptionally fused to an open reading frame encoding the fluorescent protein Venus (proDR5rev:3xVenus-N7; Heisler et al., 2005). The ectopic auxin response maxima occurred in ~1 and 33% of the wild-type and rsw4 roots, respectively, after incubation on vertical plates at the restrictive temperature for 24 h (Figure 1A). The first ectopic auxin maxima in the rsw4 roots were observed 12 h after the temperature shift before any signs of isotropic cell expansion became noticeable.

The response of plants to the gravity vector requires rapid redistribution of auxin flow resulting in alteration of spatial auxin maxima. Gravistimulation of wild-type roots leads to higher level of proDR5 activity in the outermost cell layer on the side that is perpendicular to the gravity vector (Ottenschläger et al., 2003). Consequently, any defects in the formation of an auxin gradient would impair or delay the gravitropic response. We observed that wild-type roots treated for 12 h at the restrictive temperature and then gravistimulated for 3 or 6 h by changing their orientation with respect to the gravity vector by 90° showed enhanced expression of proDR5 in the outermost cell layer of the root, accompanied by the root bending response (Figure 1B). The rsw4 seedlings showed less significant displacement of the auxin maxima within 6 h of gravistimulation and a pronounced delay in the root bending response (Figures 1B and 1C).

Since separase knockouts are embryo-lethal, we examined the gravitropic response in transgenic lines with conditionally suppressed expression of ESP, which was accomplished using an RNA hairpin construct under a dexamethasone (DEX)-inducible promoter (ESP RNAi lines; see Supplemental Figure 1A online). The hairpin construct harbors a β-glucuronidase reporter (uidA gene; GUS) also under control of the DEX-inducible promoter, which allows selection of the transgenic lines based on GUS expression in their root tips. Although the uniform expression of GUS was already visible after 2 h of induction with 20 μM DEX (see Supplemental Figure 1B online), a significant decrease of ESP mRNA level was detected after 12 h of DEX treatment (see Supplemental Figure 1C online).

Nevertheless, no discernible phenotype was observed after 12 h of induction. The longer induction with DEX phenocopied isotropic cell expansion as was previously observed in rsw4 roots incubated at the restrictive temperature for 24 to 48 h, albeit causing more severe root and root hair swelling and ectopic root hair formation (see Supplemental Figures 1D to 1F online). The gravitropic response of the ESP RNAi lines treated with DEX for 12 h and then gravistimulated for 6 h was significantly delayed (see Supplemental Figure 1G online).
Figure 1. ESP Regulates Auxin Response Maxima through Its Proteolytic Activity.
ESP is a Cys protease with a characteristic C-terminal caspase-like catalytic domain containing a conserved dyad of Cys and His (Moschou and Bozhkov, 2012). To investigate whether proteolytic activity of ESP is required for the establishment of an auxin gradient, we introduced a point mutation into the ESP open reading frame to substitute catalytic Cys for Gly (Cys1297 to Gly1297) in the ESP protein. Subsequently, this mutated ESP<sup>PD</sup> (PD for protease-dead) was introduced into the rsw4 background (Figure 1D). While pro35S:HA-ESP fully complemented the temperature-sensitive phenotype of rsw4 in terms of both root morphology and gravitropic response, the PD version pro35S:HA-ESP<sup>PD</sup> could not complement the mutant phenotype (Figures 1E to 1G). Since both rsw4;pro35S:HA-ESP and rsw4;pro35S:HA-ESP<sup>PD</sup> lines showed a minor increase of −20% in the ESP mRNA level (see Supplemental Figure 1C online), the observed effects could not be attributed to ESP mRNA level deregulation. Therefore, catalytic activity of ESP is essential for the establishment of auxin gradient in the root tip as well as the gravitropic response.

**ESP Regulates PIN2 Localization in the Root Cortex**

Considering the formation of ectopic auxin response maxima and the perturbed gravistimulation response of rsw4, we compared localization of PIN1 and PIN2 proteins in wild-type and rsw4 plants expressing proPIN1:PIN1-EGFP (for enhanced green fluorescent protein) and proPIN2:PIN2-EGFP. The time-course analysis of fluorescence pattern of PIN1-EGFP and PIN2-EGFP fusion proteins in wild-type plants incubated at the restrictive temperature revealed no apparent changes in localization of the proteins during the course of the experiment (96 h). However, in the rsw4 background, the PIN2-GFP signal on the rootward side of meristematic cortex cells already switched to the shootward side 6 h after incubation at restrictive temperature, while the shootward signal in epidermis and columella cells was not affected (Figures 2A and 2B).

The localization of PIN1 was not affected during 24 h of incubation at the restrictive temperature. Immunostaining of PIN1 and PIN2 in rsw4 plants incubated at the restrictive temperature for 24 h (Figure 2C) confirmed that endogenous PIN2 polarity in root cortex cells was significantly affected (~60 and 40% of cells showing rootward and shootward localization, respectively) in comparison with the wild type (95 and 5% of cells with rootward and shootward localization, respectively). The polarity of PIN1 was lost after 48 h of incubation at the restrictive temperature coinciding with root swelling (see Supplemental Figure 2 online). These data suggest that this loss of PIN1 polarity is a pleiotropic effect of isotropic cell expansion and perturbed tissue patterning caused by aberrant PIN2 polarity as detected at an earlier time point.

Abnormal PIN localization in rsw4 under the restrictive temperature could be a pleiotropic effect of mitotic aberrations resulting from ESP malfunction. Indeed, staining of roots incubated at restrictive temperature for 72 h with 4',6-diamidino-2-phenylindole (DAPI) revealed frequent lagging chromatids and unresolved chromosomal bridges (see Supplemental Figure 3A online). However, a significant increase of chromosomal aberrations during the time course experiment in lines expressing histone H2a fused to yellow fluorescent protein (YFP) became apparent only after 36 h of incubation at the restrictive temperature (see Supplemental Figures 3B and 3C online) and coincided with an increase in the frequency of cells with larger nuclei, root tip swelling, and loss of tissue patterning (see Supplemental Figures 3D to 3F online). The loss of correct PIN2 polarity and formation of the ectopic auxin response maxima occurred 30 and 12 h, respectively, before the accumulation of mitotic aberrations, indicating that ESP regulates cell polarity independently of its role in cell division. In addition, since the aberrant PIN2 polarity in cortex cells preceded the root swelling...
phenotype by at least 30 h, we conclude that mislocalization of PIN2 is not a pleiotropic effect of aberrant tissue morphology.

The roots from ESP RNAi lines, in addition to mitotic aberrations, contained cells with mini-nuclei, reflecting a greater degree of genome instability than in rsw4 (see Supplemental Figures 3G to 3I online). Similar to rsw4, the appearance of cells with abnormal nuclear size in the ESP RNAi lines coincided with root swelling, suggesting that the latter could be a consequence of endoreduplication (Wu et al., 2010). Therefore, the lack of ESP activity did not block entry into the G1 and S phases, which is concordant with previous observations (Wu et al., 2010).

Pharmacologically induced shootward relocation of PIN2 in the cortex cells affects the proDR5 activity pattern and suppresses the gravistimulation response (Rahman et al., 2010). Similarly, shootward localization of PIN2 in the root meristematic cortex cells of rsw4 leads to significant loss of the gravitropic response. Therefore, ESP is an important component of the pathway that regulates rootward targeting of PIN2 in root cortex cells, which is required for the maintenance of the auxin gradient and the gravitropic response.

ESP Associates with Microtubules and RabA2a-Positive Vesicles

To find out how ESP regulates PIN2 rootward cell polarity, we examined its intracellular localization in wild-type and pro35S:HA-ESP transgenic Arabidopsis roots. During interphase, ESP localized to puncta in the cytoplasm, which may coincide with microtubules (Figure 3A; see Supplemental Figure 4A online, image 1). During cell division, ESP decorates all microtubule arrays including the preprophase band, mitotic spindle, phragmoplast, and cell plate (Figure 3A; see Supplemental Figure 4A online, images 2 to 4). A similar staining pattern was observed in rsw4;pro35S:HA-ESP and rsw4;pro35S:HA-ESPrd lines grown at the restrictive temperature for 24 h (see Supplemental Figures 4B to 4D online). No staining was observed with anti-ESP in rsw4 plants grown at the restrictive temperature for 12 h, suggesting that temperature shift causes instability of the ESPrsw4 allelic protein.

In addition to microtubules, ESP colocalizes with RabA2a-YFP positive compartments, previously shown to define distinct structures in the trans-Golgi network/early endosomal compartment (Chow et al., 2008), during both interphase and telophase (Figure 3B and insets; colocalization probability approximately Pr = 0.85). Partial colocalization was also found with syntaxin KNOLLE and PIN2-EGFP-positive endosomes at the cell plate (see Supplemental Figures 5A and 5B online). No significant colocalization was observed with Golgi and trans-Golgi (see Supplemental Figures 5A and 5B online).

Despite colocalization with microtubules, ESP had no apparent effect on microtubule organization (see Supplemental Figure...
but, conversely, disorganization of microtubules is a result of the pleiotropic effect of perturbed auxin signaling and tissue patterning. These data suggest that ESP acts upstream of microtubules in the regulation of cell polarity.

The Delivery of PIN2-EGFP to the Plasma Membrane Is Slower in rsw4

Colocalization of ESP with RabA2a-positive structures and microtubules suggests that ESP might regulate microtubule-dependent delivery of PIN2 to the rootward plasma membrane in the root cortex cells. To test this hypothesis, we examined the dynamics of PIN2 delivery to the plasma membrane using fluorescence recovery after photobleaching (FRAP) of the entire rootward membrane (Figure 4). The rootward delivery of PIN2-EGFP was significantly slower in cortex cells of rsw4 compared with the wild type, whereas no difference was detected in epidermal cells (Figures 4A and 4B). The immobile fraction of PIN2-EGFP at the plasma membrane was the same in all samples analyzed, indicating that the slower fluorescence recovery rate of PIN2-EGFP did not result from altered protein retention (Figure 4C). To prove that altered fluorescence recovery of PIN2 was not a pleiotropic effect of the overall reduction of the recycling rate of plasma membrane–associated proteins, we measured the fluorescence recovery rate of the plasma membrane integral protein (PIP2A)-EGFP in the wild type and rsw4 and found no difference (Figures 4D to 4F). This suggests that ESP deficiency does not cause general membrane trafficking defects, but specifically affects polarized protein delivery. Furthermore, the delivery rates of PIN2-EGFP to the mature cell plate were the same in wild-type and rsw4 cells, consistent with the view that initial delivery of PIN2-EGFP during cell division is apolar (Men et al., 2008; see Supplemental Figure 7A online). Treatment with the protein synthesis inhibitor cycloheximide (CHX) did not affect the fluorescence recovery rate or the immobile fraction of PIN2-EGFP at the plasma membrane, indicating that rsw4 does not affect de novo–synthesized PIN2-EGFP rootward delivery (see Supplemental Figure 7B online).

To examine whether lateral diffusion of PIN2-EGFP on the plasma membrane could contribute to the observed differences in the fluorescence recovery rates of wild-type and rsw4 root cortex cells, we bleached a small area of a PIN2-EGFP–positive rootward plasma membrane (see Supplemental Figure 7C online, samples Control and CHX) and found no difference in fluorescence signal recovery between the wild type and rsw4. Next, we repeated the experiment in cells treated with trafficking inhibitors sodium azide and deoxy-D-Glc, which block the energy-dependent trafficking of molecules (Men et al., 2008). Again, the recovery rate of PIN2-EGFP fluorescent signal in the wild type and rsw4 was indistinguishable, indicating that ESP had no impact on the lateral diffusion of PIN2-EGFP (see Supplemental Figure 7C online, sample CHX-e).

rsw4 Is Hypersensitive to Brefeldin A

The recycling of PIN proteins from endosomes to the plasma membrane is sensitive to the fungal toxin Brefeldin A (BFA). BFA inhibits an ARF-GEF GNOM, which regulates intracellular sorting
and recycling of PIN1 and PIN2 to the plasma membrane (Geldner et al., 2001; Kleine-Vehn et al., 2008b) and causes accumulation of the proteins in aggregated endosomal compartments (aggresomes). The rootward delivery of PIN2 depends on the ARF-GEF pathway; consequently, rootward localization of PIN2 is more sensitive to BFA than shootward localization (Feraru and Friml, 2008; Kleine-Vehn et al., 2009; Rahman et al., 2010). Furthermore, low concentrations of BFA cause a rootward-to-shootward shift of PIN2 in root cortex cells and perturb the gravistimulation response (Rahman et al., 2010) in the same way as we observed in rsw4, implying higher sensitivity of rsw4 to BFA.

Treatment of wild-type and rsw4 roots with 50 µM BFA for 1.5 h resulted in internalization of PIN2-EGFP to BFA compartments in both wild-type and rsw4 (Figure 5A; see Supplemental Figure 8A online), although the internalization occurred more quickly in rsw4 (see Supplemental Figure 8A online, graph). The effect of BFA is reversible, and localization of PIN2 in the plasma membrane recovers after BFA washout (Geldner et al., 2001). In our experiments, PIN2-EGFP localization in the wild-type cells was almost completely restored as early as only 1 h after washout, while in the rsw4 cells, PIN2-EGFP positive BFA compartments remained (Figure 5A; see Supplemental Figure 8A online). Furthermore, a similar effect was observed in ESP RNAi;proPIN2:PIN2-EGFP lines (see Supplemental Figure 9 online). To verify that the observed difference was independent of the PIN2-EGFP

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degradation rate, wild-type and rsw4 lines were incubated in the dark for 4 h, and the intensity of the GFP signal was measured in the vacuoles where degradation of PIN2 takes place. The signal was equal in the vacuoles of both the wild type and rsw4, indicating that ESP does not affect PIN2 degradation (see Supplemental Figure 8B online). The recovery of PIN2 localization on the plasma membrane after 3 h treatment with BFA followed by 1 h washout occurred only in rsw4 complemented with the functional HA-ESP, but not with the protease-dead mutant HA-ESP<sup>PRO</sup> (see Supplemental Figure 8C online).

The gravitropic response of rsw4 roots was also hypersensitive to BFA. The plants grown on medium supplemented with BFA for 2 d were then incubated at the restrictive temperature for 12 h and subjected to gravitropic stimulation (Figure 5B; Rahman et al., 2010). While ~50% reduction of the gravitropic response was apparent in wild-type seedlings treated with 3 µM BFA, a similar effect in the rsw4 seedlings was achieved with only 1 µM BFA treatment (Figure 5B). Taken together, the suppressed rootward targeting of PIN2 and the hypersensitivity of rsw4 to BFA suggest the importance of ESP catalytic activity in the regulation of the ARF-GEF GNOM-dependent PIN2 trafficking pathway.

Endocytosis Is Not Affected by ESP Failure

In addition to exocytosis, endocytosis plays an important role in the polar localization of PIN2 (Men et al., 2008). To examine whether ESP regulates endocytosis, we measured the overall rate of internalization of the endocytic tracer FM4-64 in wild-type and rsw4 roots (Ueda et al., 2001; Grebe et al., 2003; Dhonukshe et al., 2007; Men et al., 2008). Pulse labeling with FM4-64 followed by time-lapse imaging of the fluorescent signal in the root epidermis and cortex cells revealed similar dynamics of the appearance of FM4-64–positive endosomes and the net FM4-64 internalization rate in the wild type and rsw4 (Figures 6A and 6B). Furthermore, no mislocalization of clathrin light-chain-GFP (CLC2-GFP) (Konopka et al., 2008) was observed in the rsw4 or ESP RNAi lines (see Supplemental Figure 10A online, control panels). The changes in CLC2-GFP localization after treatment with the inhibitor of clathrin-mediated endocytosis tyrphostin A23 (Banbury et al., 2003; Konopka et al., 2008) were indistinguishable in the wild-type, rsw4, and ESP RNAi lines (see Supplemental Figure 10A online, Tyr A23 panels). The inactive analog of tyrphostin A23, tyrphostin A51, had no effect on the localization of CLC2-GFP (see Supplemental Figure 10A online, Tyr A51 panels).

To investigate the role of ESP in endocytosis during cell division, we examined the localization of KNOLLE in wild-type and rsw4 plants incubated for 12 to 72 h at the restrictive temperature. During cytokinesis, KNOLLE is removed from the lateral cell membranes via DRP1a– (for DYNAMIN RELATED PROTEIN1a) and clathrin-mediated endocytosis, remaining only on the cell plate (Boutté et al., 2010). A significant reduction of endocytosis during cytokinesis would result in the retention of KNOLLE on the lateral membranes. However, no apparent difference in KNOLLE localization was observed between the wild type and rsw4 (see Supplemental Figure 10B online). Likewise, no apparent difference in KNOLLE localization was observed between wild-type and ESP RNAi lines after 12 h induction with DEX (see Supplemental Figure 10B online). We also introduced KNOLLE-GFP into both the wild-type and ESP RNAi background and found that after induction with DEX for 24 h or longer, the frequency of cells with KNOLLE-GFP was dramatically reduced in the ESP RNAi lines due to the blocking of the transition from metaphase to telophase in all dividing cells (see Supplemental Figure 10C online).

ESP Regulates the Dynamics of Cell Plate Proteins

Considering the localization of ESP on the phragmoplast microtubules and cell plate after microtubules disassembly, we hypothesized that ESP might be involved in the regulation of vesicular delivery to the cell plate. To investigate this possibility, we performed FRAP analysis of three markers of vesicular compartments (KNOLLE, CLC2, and RabA2a), which accumulate at the cell plate (Lukowitz et al., 1996; Chow et al., 2008; Van

Figure 6. Endocytosis Is Not Altered in rsw4.

(A) FM4-64 internalization in wild-type (WT) and rsw4 root cells pulsed for 5 min (time 0) and then analyzed during 18 min (time in minutes is shown in the top left corners). Bars = 5 µm.

(B) Quantification of FM4-64 internalization rate, as a cytoplasm/plasma membrane ratio of fluorescence in wild-type and rsw4 root cells. The data show mean ± so of triplicate experiments, each containing at least 20 seedlings.

[See online article for color version of this figure.]
The recovery of photobleached fluorescence signal on a region of the cell plate depends on two simultaneous processes: delivery or association of new cytoplasmic molecules and lateral diffusion of preexisting molecules along the cell plate. FRAP on a small region of the cell plate revealed that KNOLLE-GFP had a recovery pattern typical for a protein with lateral diffusion, when recovery depends mostly on preexisting fluorescent molecules diffusing along the cell plate (see Supplemental Figure 11A online). To visualize de novo delivery of new molecules to the cell plate, we excluded the contribution of lateral diffusion by bleaching the whole cell plate. Kymograph analysis revealed that KNOLLE-GFP recovery was random along the cell plate, suggesting that in this case, recovery depends on the delivery of new fluorescent molecules (see Supplemental Figure 11B online). The random recovery pattern was also observed for RabA2a-YFP (see Supplemental Figure 11C online).

The recovery rates (half-times) of all three markers in the wild type were similar at both the permissive and restrictive temperature, and there was no significant difference between values in wild-type and rsw4 cells measured at the permissive temperature (see Supplemental Figure 12 online). In the apparently nonexpanding cell plates connected to the mother cell walls at the later stages of cytokinesis, the recovery rates of RabA2a-YFP and CLC2-GFP in the rsw4 roots was ~2 and 7 times slower, respectively, than in the control. The average recovery rate of KNOLLE-GFP was similar to that of the control samples (see Supplemental Figure 12 online). However, we noticed higher standard deviation values than in the case of the former two markers, indicating that association of KNOLLE-GFP with the cell plate is more variable, and this may depend on the stage of cell plate assembly. To address this point, we measured the recovery rates of KNOLLE-GFP during cell plate expansion and observed ~4 times slower recovery in rsw4 compared with the wild type (Figure 7). This suggests that either additional ESP-independent trafficking pathways are activated to recycle KNOLLE during cell plate maturation or the ESP-dependent pathway is deactivated upon completion of the cell plate expansion. In contrast with KNOLLE, the recovery rates for RabA2a-YFP and CLC2-GFP were similar in expanding and maturing cell plates (see Supplemental Figure 13B online).

Kymographs revealed that CLC2-GFP in rsw4 lines persisted on the cell plate longer than in the wild type (see Supplemental Figure 11D online). Similar kymographs were obtained in experiments where the FRAP step was omitted (see Supplemental Figure 11D online, -FRAP), indicating that deregulation of ESP causes a delay in maturation and/or detachment of clathrin-coated vesicles. We suggest that ESP regulates trafficking of proteins to the cell plate during the expansion phase and cycling of peripheral membrane proteins during cell plate maturation.

Deactivation of ESP Results in Cytokinesis Failure

The decreased activity of RabA2a correlates with incomplete cell plate formation in Arabidopsis roots (Chow et al., 2008). The perturbation of vesicular trafficking to the expanding cell plate in rsw4 could result in a slower rate of cell plate expansion and incomplete cell plate formation. We measured the cell plate expansion rate by staining cell membranes with FM4-64 and found that, indeed, the expansion rate was significantly reduced in rsw4 (Figure 8A), while the phragmoplast morphology in rsw4 and wild-type plants was indistinguishable (see Supplemental Figure 14 online). Kymographs of cell plate expansion in WT; proRabA2a::YFP-RabA2a and rsw4;proRabA2a::YFP-RabA2a plants revealed correct formation of the cell plate leading edges (Figures 8B and 8C). However, YFP-RabA2a signal was homogeneously spread along the cell plate in rsw4, compared with more concentrated signal at the leading edges of cell plates in the wild type (Figure 8C, graph). As shown by the immunolocalization experiments, ESP persists at the cell plate following microtubule disassembly, perhaps to regulate maturation events, such as removal of RabA2a proteins, and to re-instate normal vesicular recycling.

Incomplete cell plate formation (cytokinetic failure) was observed in rsw4 and rsw4;pro35S:HA-ESP<sup>PD</sup> plants following 12 h incubation at the restrictive temperature (Figure 9, rsw4), which is consistent with the role of ESP in the regulation of cell plate assembly. The frequency of cells with cell wall stubs or wavy cell plates was significantly higher in the RNAi lines induced for 12 h (Figure 9, RNAi). Taken together, these data demonstrate that ESP is required for cell plate assembly.
are known as key players in this process, but what coordinates and brings them together remains unknown. Here, we show that ESP functions in the regulation of cell polarity in Arabidopsis. Several lines of evidence support this conclusion. First, compromised ESP activity results in the loss of anisotropic cell expansion and swelling of root cells, including root hairs. Second, there is a delayed gravistimulation response in both the rsw4 background and inducible ESP RNAi lines. Proper gravistimulation response was restored in the rsw4 background by introducing HA-ESP, while the protease-dead version HA-ESP<sup>PD</sup> failed to rescue the rsw4 phenotype, demonstrating that proteolytic activity of ESP is essential for its role in the establishment of cell polarity. Third, perturbation of polar auxin flow in the root tips of rsw4 was manifested by the appearance of ectopic auxin response maxima and delayed reestablishment of auxin response maxima following gravistimulation. Fourth, localization of PIN2 carrier, which is responsible for the maintenance of the auxin flow, switched from the rootward side of the plasma membrane to the shootward side in the rsw4 root cortex cells within the meristematic zone.

The localization pattern of ESP points to at least two distinct functions of the protein performed during cell division and during interphase, respectively. Initially, ESP was identified as an executioner of daughter chromatid segregation (Ciosk et al., 1998; Uhlmann et al., 1999). This function requires proteolytic activity of ESP and appears to be conserved in all eukaryotes, from yeasts to vertebrates, as ESP knockouts are lethal in all model systems, including Arabidopsis (Liu and Makaroff, 2006; Moschou and Bozhkov, 2012). In agreement with this function, ESP binds to spindle microtubules during prophase, metaphase, and anaphase, to the phragmoplast microtubules, and eventually to the cell plate. In addition, ESP shows transient colocalization with RabA2a-positive structures. The localization of ESP varies across species. For example, yeast ESP associates with spindle poles and anaphase spindle microtubules, whereas human ESP was found only on the spindle poles during metaphase and in the cytoplasm from the onset of anaphase (Jensen et al., 2001; Chestukhin et al., 2003). In the cytoplasm, human ESP was found associated with vesicular compartments of the secretory pathway (Bacac et al., 2011). In Caenorhabditis elegans, ESP localizes on spindle poles and chromosomes during metaphase and anaphase and translocates to the cleavage furrow during cytokinesis (Bembenek et al., 2010), where it associates with the cortical granules prior to exocytosis (Bembenek et al., 2007). Therefore, ESP may have another function in the regulation of vesicle trafficking along microtubules, as exemplified by microtubule- and GNOM-dependent targeting of PIN2 to the rootward side of meristematic root cortex cells (Kleine-Vehn et al., 2008a).

Indeed, measurement of PIN2 dynamics at the plasma membrane of root cortex cells by FRAP shows that ESP deficiency leads to slower delivery of PIN2 to the rootward side of the cells. At the same time, ESP has no apparent role in the regulation of lateral diffusion or retention of PIN2 or in PIN2 dynamics at the shootward side of root epidermal cells. GNOM-dependent rootward localization of PIN2 is sensitive to low concentrations of BFA (up to 10 µM) (Rahman et al., 2010), and inhibition of this pathway leads to shootward relocation of PIN2 in the meristematic root cortex cells accompanied by partial loss of the...
gravistimulation response, showing striking similarity to the effect of ESP mutation. Treatment of roots with higher concentrations of BFA induced accumulation of PIN2 in BFA compartments in the cells of both rsw4 and wild-type plants, but the fluorescence of BFA compartments in rsw4 was stronger. Similar observations were reported for exocytosis mutants pp2a (for protein phosphatase 2a) and bex5/Rab1b (for BFA-visualized exocytic trafficking defective/RAS GENES FROM RAT BRAIN A1b), suggesting that exocytosis is perturbed in rsw4 (Rahman et al., 2010; Feraru et al., 2012). In agreement with this hypothesis, relocation of PIN2 from the BFA compartments back to the plasma membrane after BFA washout was significantly delayed in rsw4. Therefore, we conclude that ESP regulates ARF GNOM and trafficking of PIN2 from recycling endosomes to the rootward plasma membrane.

The polar localization of PIN proteins requires simultaneous activity of both exo- and endocytosis. For example, the reduced rate of endocytosis in the Arabidopsis cpi1-1 (for cyclopropylsterol isomerase1-1) mutant inhibits reestablishment of polar PIN2 localization following cytokinesis (Men et al., 2008). The slower endocytosis in interphase cells leads to a slower internalization rate of the fluorescent dye FM4-64, while during mitosis, defective endocytosis results in localization of the normally cell plate–restricted protein KNOLLE to the lateral sides of the cells (Men et al., 2008). We used both FM4-64 and KNOLLE as markers of endocytic defects (Boutté et al., 2010) and in contrast with drp1a and cpi1-1 found no significant differences between the wild-type, rsw4, and ESP RNAi lines. Therefore, ESP is unlikely to be a regulator of endocytosis and overall membrane recycling but rather seems to target a specific trafficking pathway different from the ones reported for drp1a and cpi1-1.

The aberrations of the GNOM-dependent exocytic pathway in rsw4 may be a consequence of microtubule disorganization. Previously, no changes were reported in the orientation of transverse microtubules in rsw4 (Wiedemeier et al., 2002), while in a later study, disorganization of microtubules become apparent after 15 h of incubation at the restrictive temperature (Wu et al., 2010). Here, we found no discernible disorganization of cortical microtubules in rsw4 cells for up to 36 h of incubation at the restrictive temperature, perhaps due to different plant growth conditions. Longer incubations at the restrictive temperature led to disorganization of the cortical microtubule network coincident with a surge in mitotic aberrations, cell swelling, and loss of PIN1 polarity. The loss of transverse microtubule organization might be responsible for the cell swelling; however, what causes disorganization of microtubules is not clear. Wu et al. (2010) suggested that the latter could be a consequence of accumulation of CYCB1;1. Ectopic overexpression of CYCB1;1 in tobacco (Nicotiana tabacum) plants causes disorganization of cortical microtubules and cell swelling (Weingartner et al., 2004). Since the accumulation of CYCB1;1 occurred only after 15 h of incubation at the restrictive temperature (Wu et al., 2010), long after the switch of PIN2 polarity, the disorganization of microtubules is more likely to be a downstream effect of the loss of cell polarity and not the cause of the perturbed vesicle trafficking.

Interaction of ESP with microtubules during prophase and metaphase is consistent with its role in orchestrating karyokinesis, but persistence of ESP on the phragmoplast microtubules and association with the cell plate highlights a function of ESP during plant cytokinesis. Multiple components of endo- and exocytic pathways (e.g., KNOLLE, dynamin DRP1A, RabA2a,
exocyst, and clathrin) have been localized to the phragmoplast midzone, providing compelling evidence that vesicle recycling pathways contribute to cell plate assembly (Lukowitz et al., 1996; Van Damme et al., 2006; Chow et al., 2008; Fendrych et al., 2010; Mravec et al., 2011). This conclusion has been further corroborated using mutants of exocytic (KNOLLE; Lukowitz et al., 1996), exocyst (Fendrych et al., 2010), and endocytic (DRP1a; Collings et al., 2008) pathways. The reduced dynamics of KNOLLE, CLC2, and RabA2a at the expanding cell plate and the occurrence of cell wall stubs in rsw4 and ESP RNAi plants indicate that ESP regulates a pathway of vesicle trafficking required for cell plate assembly. During cell plate maturation, the recovery of CLC2 and RabA2a was still significantly reduced, while the recovery of KNOLLE was similar to the control. This suggests that separate vesicle delivery and recycling by several independent pathways: One regulates KNOLLE during the cell plate expansion stage, while different pathway(s) regulate CLC2 and RabA2a. The role of ESP in cytokinesis appears to be evolutionarily conserved, as the C. elegans homolog of RabA2a, Rab11, colocalizes with ESP in the cleavage furrow during cytokinesis, and depletion of ESP results in persistence of GFP-Rab11 at the cleavage furrow and the midbody leading to cytokinetic failure (Bembenek et al., 2010). Furthermore, similar to the situation in interphase cells, organization of the phragmoplasts in ESP mutants was indistinguishable from the control, demonstrating that the inhibition of cell plate assembly is not a consequence of microtubule disorganization.

Our data show that the plant homolog of separase, ESP, is essential for three fundamental cellular processes. The first process is daughter chromatin separation during the metaphase to anaphase transition and mitotic progression. The second process is the partitioning of daughter cells during cytokinesis. Unlike the former role, this role may not be evolutionarily conserved and so far has only been clearly demonstrated for C. elegans (Bembenek et al., 2010). The third role lies in the establishment and maintenance of cell polarity and tissue patterning. This role is not plant specific either, as the Drosophila melanogaster ESP homolog regulates posterior-anterior axis formation during embryogenesis (Rapleye et al., 2002), but its functional conservation in other lineages remains unknown. Considering the apparent endoreduplication events in ESP mutants, ESP does not play a role during the G1 and S phases of the cell cycle (our results; Wu et al., 2010).

The loss of cell polarity in rsw4 plants takes place within 36 h of incubation at the restrictive temperature and is followed by isotropic cell expansion. This is preceded by the loss of PIN2 polarity after 6 h, appearance of the ectopic auxin response maxima after 12 h, and mitotic failures after 36 h. The isotropic cell expansion is accompanied by disorganization of interphase microtubules and pleiotropic mislocalization of PIN1 protein in the cells after 48 h. This time line demonstrates that the loss of cell polarity does not result from disorganization of cortical microtubules, mitotic failure, and incomplete cytokinesis. In turn, disorganization of cortical microtubules appears to be a consequence of the loss of cell polarity. The swelling of already differentiated cells (e.g., root hairs) at the time of induction of ESP RNAi lines further corroborate this conclusion.

In metazoans, the Cys proteases calpains are integral components of the cell polarization machinery (Bórquez and González-Billault, 2011). Being essential for embryogenesis and seed development, plant calpain-like protease Dek1 (for Defective kernel1) has not been implicated in the regulation of cell polarity (Lid et al., 2005). Our work demonstrates that the regulation of cell polarity and cytokinesis in plants is taken over by a member of caspase-related proteases, ESPs, and highlights the evolutionarily conserved role of proteases in the regulation of this process. Since catalytically inactive ESP fails to rescue the rsw4 phenotype, the regulation of GNOM-dependent recycling of PIN proteins from endosomes to the plasma membrane requires proteolytic cleavage of an as yet unknown substrate(s) by ESP. Identification of the natural targets of ESP will be the next critical step to advance our understanding of the molecular mechanisms coordinating vesicle trafficking and cell polarity.

METHODS

Plant Material and Growth Conditions

Arabidopsis thaliana plants were grown on vertical plates containing half-strength Murashige and Skoog (MS) medium supplemented with 1% (w/v) Suc and 0.7% (w/v) plant agar, at 20°C (permissive temperature) or 28°C (restrictive temperature), 16-h light/dark cycle, and light intensity 150 µE m⁻² s⁻¹. The root swelling phenotype was observed in homozygous rsw4 plants within 3 d of incubation at 28°C. The following transgenic fluorescent protein marker lines in Columbia-0 (Col-0) background were used: proRabA2a:YFP-RabA2a (Chow et al., 2008), p35S:GFP-RAB-F2b (Jailaïs et al., 2006), pro35S:N-ST-YFP and pro3SS:NAG1-EGFP (Grebe et al., 2003), proPIN1:PIN1-GFP (Benková et al., 2003), proPIN2:PIN2-EGFP (Xu and Scheres, 2005), and pro35SS:GFP-PIP2a (Cutler et al., 2000). The proKNOLLE:GFP-KNOLLE was in a Landsberg erecta/Niederzenz background (Reichardt et al., 2007), proCLC2:CLC2-EGFP (Konopka et al., 2008) was in Wassilewskija background, and pro35S:srsmRS:GFP-TUB6, pro3SS:srsmRS-GFP-TUA6 (Nottingham Arabidopsis Stock Centre; N6550) and pro35SS:GFP-TUB9 (Nottingham Arabidopsis Stock Centre; M84706) were in Col-0 background. Gravistimulation assays were performed by incubating plates containing 5-d-old seedlings grown vertically for 12 h under the restrictive temperature and subsequently reorienting the plates by 90° under the same conditions.

Molecular Biology

All oligonucleotide primers used in this study are shown in Supplemental Table 1 online. ESP was amplified by PCR from a cDNA derived from 2-week-old leaves of Arabidopsis Col-0 plants. The 5′-end 4.6-kb DNA fragment was amplified using primers Fw428AtESP and RvAtESPdomA and cloned into a pJET vector (Fermentas). The overlapping 3′-end 2.6-kb fragment was amplified by Fw4428AtESP and RvAtESPAscI and then cloned into pJET. The overlapping region contained Spei site. The 5′ fragment was reamplified from pJET by PCR and cloned into the pTOPO/D vector (Invitrogen) giving rise to the pTOPO/D-AtESP 4.6 kb. The remaining part of ESP was reamplified by Fw428AtIESP and RvAtIESPAscI from the corresponding pJET vector, digested by Spei-Ascl, and cloned into Spei-Ascl sites of pTOPO/D-AtESP 4.6-kb vector giving rise to full-length clone pTOPO/D-AtESP 6.5 kb. All plasmids and derived constructs were verified by sequencing using the primers AISE-F1 to AISE-F9.

For expressing N-terminal HA-epitope tag fusions under the control of 3SS promoter, ESP was cloned to the destination vectors pGWB615 and pGWB15 (Nakagawa et al., 2007) using Gateway technology (Invitrogen).
Mutations were inserted using the Quickchange Stratagene mutagenesis kit and the primers MutATSE1 and MutATSE2 according to the manufacturer’s instructions (Stratagene).

For constructing ESP RNAi lines, a 435-bp fragment of ESP cDNA was amplified using the primers AtESPNA2Fw and AtESPNA2Fw. The fragment was introduced by Gateway technology (Invitrogen) to the inducible pOpOff2-KAN vector (Craft et al., 2005).

### Plant Transformation

*Arabidopsis* Col-0 plants were transformed as described previously (Clough and Bent, 1998) using Agrobacterium tumefaciens strain GV3101. In all experiments, plants from T2 and T3 generations were used. Transgenic plants were confirmed by PCR.

### Preparation of Antibodies

A 1674-bp-long C-terminal fragment of pTOPO/D-ATESP 6.5 kb was amplified with the primers FwAtESP-dC and RvAtESP-dC, and it was introduced into the entry pDONR/Zeo (Invitrogen) vector using the Gateway BP reaction. Subsequently, the insert was introduced into pDEST-TTH1 (Hammarström et al., 2002) and pGAT4 (Ketelaar et al., 2004). The pDEST-TTH1-ATESP and pGAT4-ATESP constructs were transformed in BL21 (DE3) RIL (Stratagene) Escherichia coli cells. Preparation of maltose binding protein (MBP)-tagged recombinant proteins was performed as described previously (Moschou and Roubelakis-Angelakis, 2011). Briefly, protein expression was induced at OD_{600} = 0.5 by adding 0.05 mM to 1 mM isopropyl β-D-thiogalactopyranoside to Luria-Bertani medium supplemented with 100 μg/mL ampicillin and 2 g L⁻¹ Glc. The cells were harvested by centrifugation at 2500g for 20 min at room temperature and frozen overnight at ~80°C. Cells were dissolved in 10 mL of MBP buffer (20 mM Tris, pH 7.4, 400 mM NaCl, 1 mM EDTA, and 0.5 mM PMSF) and lysed at 4°C in a sonicator using four cycles of 15 s to 20 s. Cell debris was removed by centrifugation at 10,000 rpm for 20 min at 4°C, and the supernatant was filtered through Miracloth and passed through amyllose resin (Bioblasts) at 4°C. Protein was eluted using MBP buffer supplemented with 20 mM maltose. Preparation of His-tagged recombinant proteins from pGAT4-AtESP was performed according to the manufacturer’s instructions (Qiagen). The antisera was raised in mice and rabbits using the C-terminal ESP fragment as the antigen.

### Immunocytochemistry and Imaging

*Arabidopsis* roots were fixed for 60 min at room temperature with 4% (w/v) paraformaldehyde in 0.1 M PIPES, pH 6.8, 5 mM EGTA, 2 mM MgCl₂, and 0.4% Triton X-100. The fixative was washed away with phosphate buffered saline buffer and supplemented with Tween 20 (PBST) and cells were treated for 8 min at room temperature with a solution of 2% (w/v) Driselase (Sigma-Aldrich) in 0.4 M mannitol, 5 mM EGTA, 15 mM MES, pH 5.0, 1 mM PMSF, 10 μg mL⁻¹ leupeptin, and 10 μg mL⁻¹ pepstatin A. Thereafter, roots were washed twice 10 min each in PBST and in 1% (w/v) BSA in PBST for 30 min and incubated overnight with a primary antibody. The primary antibodies were mouse anti-HA (diluted 1:500), rabbit anti-ESP (1:500), rat anti-tubulin YL1/2 (1:200; Sigma-Aldrich), rabbit anti-KNOXLLE (1:1000) (Łukowicz et al., 1996), rabbit anti-PIN1 (1:150), and guinea pig anti-PIN2 (1:150). The specimens were then washed three times for 90 min in PBST and incubated overnight with goat anti-mouse tetramethylrhodamine isothiocyanate or anti-rabbit fluorescein isothiocyanate (FITC) conjugated secondary antibodies diluted 1:200. After washing in the PBST buffer, the specimens were mounted in Vectashield mounting medium (Vector Laboratories).

For plasma membrane staining and endocytosis measurements, seedlings were incubated in liquid half-strength MS medium (LMS; supplemented with 1% [w/v] Suc, pH 5.7) supplemented with 2 μM FM4-64 (Molecular Probes; made from a 2 mM stock in DMSO) for 5 min on ice. The roots were washed two times in ice-cold LMS medium, mounted in LMS medium, and observed immediately.

The samples were examined using Zeiss510, Zeiss710, Zeiss780, or Leica SP5 confocal microscopes.

### Drug Treatments

All drugs were from Sigma-Aldrich, unless otherwise stated. Several 3- to 5-d-old seedlings were submersed in LMS containing corresponding drugs. BFA was dissolved in DMSO and used at 10 μM for 2 h or 50 μM for 1 h. Washout experiments were performed with LMS. Tyrphostin A23 or tyrphostin A51 (Santa Cruz Biotechnology) were dissolved in DMSO and used at 50 μM in LMS for 5 min. CHX was added from a 50 mM aqueous stock to a final concentration of 50 μM. Treatment of seedlings with 0.02% (w/v) sodium azide and 50 mM 2-deoxy-o-Glc was as previously described (Men et al., 2008). Briefly, seedlings were incubated in inhibitor-containing LMS for 30 min and subsequently examined in the presence of the inhibitors. DEX (Sigma-Aldrich) was dissolved in DMSO at 78 mM. Transgene induction was performed on vertical MS plates supplemented with 20 μM DEX.

### Image and Statistical Analysis

The image analysis was done using ImageJ v 1.41 software http://rsb.info.nih.gov/j/index.html. The kymographs were generated using the ImageJ plug-in written by Jens Riehelt (FMI, Basel) and Arne Seitz (EMBL, Heidelberg). The recovery rate was calculated by the single exponential fit as described previously (Chang et al., 2005). Colocalization analyses were performed as described previously (French et al., 2008) using Pearson statistics. Spearman analyses gave similar results. Root curvature was measured by Adobe Illustrator v. CSS (Adobe) on digital photographs. Statistical analysis was performed with SPSS v14 (www.spss.com).

### In Situ GUS Assay

In situ detection of GUS was performed essentially as described earlier (Fincato et al., 2012). DEX-induced ESP RNAi roots were stained for 10 min at 37°C, and the intensity of the signal was quantified by densitometry of digital photographs. ESP RNAi DEX untreated roots did not show GUS staining even after 2 d of incubation at 37°C.

### Quantitative RT-PCR of ESP mRNA Levels

One hundred root tips were used for each RNA extraction, and 400 ng RNA were used per RT reaction with a Maxima kit (Fermentas, Thermo Fisher Scientific). Out of the list of genes stably expressed throughout developmental stages of Arabidopsis (Czechowski et al., 2005), two, PPA2 (AT1G13320.1) and RNA helicase (AT1G58050.1), were used for normalization (Minina et al., 2013). Quantitative PCR reactions were performed using the iQ5 PCR thermal cycler (Bio-Rad) and DyNaMo Flash SYBR Green qPCR kit (Finnzymes, Thermo Fisher Scientific). For quantification of ESP expression, we used the 2^−ΔΔCT (cycle threshold) method (Livak and Schmittgen, 2001) and three biological replicates.

### Protein Gel Blot Analyses

One hundred milligrams of leaf material was mixed with 100 μL of urea extraction buffer (4 mM urea, 100 mM DTT, and 1% [w/v] Triton X-100) and incubated on ice for 10 min. The samples were boiled with Laemmli sample buffer for 10 min and centrifuged at 13,000 rpm for 15 min. Equal amounts of each supernatant were loaded on 10% poly-acrylamide gels.
and blotted on a polyvinylidene difluoride (PVDF) membrane. Anti-HA and anti-ACTIN were used at a dilution of 1:1000; anti-rabbit horseradish peroxidase conjugate (Amersham, GE Healthcare) was used at dilution 1:5000. The reaction was developed for 8 h using an ECL Prime kit (Amersham, GE Healthcare) and detected in an LAS-3000 luminescent image analyzer (Fujifilm, Fuji Photo Film).

FRAP Experiments

Five-day-old seedlings were used for the FRAP experiments. Seedlings were grown on sterile CellView cell culture plates with glass bottoms (35 mm; Greiner Bio One), containing 1 mL of half-strength MS, 1% (w/v) Suc, and 0.3% (w/v) of electrophoresis grade agarose. For inhibitor treatments, plants were placed on plates containing the corresponding inhibitor dissolved in LSM medium. GFP-KNOLLE, RabA2a-YFP, CLC2-GFP, and PIN2-GFP fluorescence was detected using a water- or oil-corrected ×40 objective. During analyses, FRAP mode of Zeiss510meta, Zeiss710 ZEN, or Zeiss780 ZEN software was set up for acquisition of one prebleach image, one bleach scan, and 40 postbleach scans (20 for PIN2-GFP). For FRAP experiments of GFP-KNOLLE over the whole division plane, the width of the bleached region was constant at 2 µm; Greiner Bio One), containing 1 mL of half-strength MS, 1% (w/v) Suc, and 0.3% (w/v) of electrophoresis grade agarose. For inhibitor treatments, plants were placed on plates containing the corresponding inhibitor dissolved in LSM medium. GFP-KNOLLE, RabA2a-YFP, CLC2-GFP, and PIN2-GFP fluorescence was detected using a water- or oil-corrected ×40 objective. During analyses, FRAP mode of Zeiss510meta, Zeiss710 ZEN, or Zeiss780 ZEN software was set up for acquisition of one prebleach image, one bleach scan, and 40 postbleach scans (20 for PIN2-GFP). For FRAP experiments of GFP-KNOLLE over the whole division plane, the width of the bleached region was constant at 2 µm, and the length was adjusted according to the length of each cell plate. The following settings were used for photobleaching: 10 to 20 iterations for GFP-KNOLLE, RabA2a-YFP, and CLC2-GFP; 10 to 60 s per frame; 10 to 20 iterations for GFP-KNOLLE, RabA2a-YFP, and CLC2-GFP; and 0.3% (w/v) of electrophoresis grade agarose. For inhibitor treatments, plants were placed on plates containing the corresponding inhibitor dissolved in LSM medium. GFP-KNOLLE, RabA2a-YFP, CLC2-GFP, and PIN2-GFP fluorescence was detected using a water- or oil-corrected ×40 objective. During analyses, FRAP mode of Zeiss510meta, Zeiss710 ZEN, or Zeiss780 ZEN software was set up for acquisition of one prebleach image, one bleach scan, and 40 postbleach scans (20 for PIN2-GFP). For FRAP experiments of GFP-KNOLLE over the whole division plane, the width of the bleached region was constant at 2 µm, and the length was adjusted according to the length of each cell plate. The following settings were used for photobleaching: 10 to 20 iterations for GFP-KNOLLE, RabA2a-YFP, and CLC2-GFP; 10 to 60 s per frame; 100% transmittance with the 458- to 514-nm laser lines of argon laser. Pre- and postbleach scans were at minimum possible laser power (1.4 to 20% transmittance) for the 488 nm and 0% for all other laser lines; 512 × 512 pixel format; and zoom factor of 5.1. Analysis of fluorescence intensities during FRAP was performed in regions of interest (ROIs) corresponding to the size of the bleached region. One ROI was measured outside the bleached region to serve as the background. The fluorescence recovery values were determined, then the background values were subtracted from the fluorescence recovery values, and the resulting values were normalized against the first postbleach time point. For the analysis of lateral mobility of GFP-KNOLLE, fluorescence recovery values were corrected for the artificial loss of fluorescence using values from the neighboring cells. At least eight cells from different roots were analyzed for each FRAP experiment. For the analysis of lateral mobility of PIN2-GFP in the cell plate, the photobleached area was set up as a 2-µm rectangle in the middle of the cell plate. Postbleach images were acquired every 20 s over 6 min. After subtraction of background values, the artificial loss of fluorescence in the bleached ROI was corrected using fluorescence signal intensity values measured over the entire cell.

Accession Numbers

Sequence data from this article can be found in the GenBank/EMBL data libraries under the following accession numbers: ESP, AT4G22970; Rab2a, AT1G09630; Rab2b, AT4G19640; PIN1, AT1G73590; PIN2, AT5G57090; Pip2a, AT3G53420; Knolle, AT1G08560; CLC2, AT2G40060; TUB6, AT5G12250; TUA6, AT4G14960; and TUB9, AT4G20890.

Supplemental Data

The following materials are available in the online version of this article.

Supplemental Figure 1. Molecular and Phenotypic Analysis of Inducible ESP RNAi Lines.

Supplemental Figure 2. Abnormal Localization of PIN1 (Red) and PIN2 (Green) in the rsw4 Roots after Incubation at the Restrictive Temperature for 48 h.

Supplemental Figure 3. Mitotic Aberrations and Developmental Defects in rsw4 and ESP RNAi Lines.

Supplemental Figure 4. HA-ESP and HA-ESPDD Colocalize with Microtubules.

Supplemental Figure 5. Colocalization Analysis of ESP with Microtubules, Golgi, Cell Plate, Late Endosomes, and PIN2.

Supplemental Figure 6. Loss of Transverse Orientation of Cortical Microtubule in Root Epidermal Cells of rsw4.

Supplemental Figure 7. Apolar and Biosynthetic Delivery of PIN2-EGFP Remains Unaffected in rsw4.

Supplemental Figure 8. Exocytosis of PIN2-EGFP Is Affected in rsw4, but the Degradation Pathway Is Normal.

Supplemental Figure 9. ESP RNAi Lines Are Defective in Protein Trafficking to the Plasma Membrane.

Supplemental Figure 10. ESP Deficiency Does Not Affect Clathrin (CLC2) or KNOLLE Localization.

Supplemental Figure 11. FRAP and Kymograph Analysis of KNOLLE, Clathrin CLC2, and Rab2a at the Cell Plate.

Supplemental Figure 12. FRAP Analyses of KNOLLE, CLC2, and Rab2a in Maturing Cell Plates in the Wild-Type and rsw4 Samples.

Supplemental Figure 13. FRAP Analysis of CLC2 and Rab2a at the Expanding and Maturing Cell Plates in Wild-Type Cells.

Supplemental Figure 14. Phragmoplast Structure in Wild-Type and rsw4 Plants.

Supplemental Table 1. List of Primers Used in This Study.

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AUTHOR CONTRIBUTIONS


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Correction


In the original publication, the enlarged images of Pin1 and Pin2 localization in Figure 2C do not correspond to the boxed areas in the lower magnification panels. Here, we present the corrected version of this figure.

Figure 2. ESP Regulates PIN2 Localization.

(C) Immunostaining of PIN1 (small boxes b and d; red online) and PIN2 (small boxes a and c; green online) in the root tips of wild-type and rsw4 plants grown at the restrictive temperature. Boxed areas in center panels are enlarged and shown to the right (Pin1) and left (Pin2). Arrows indicate polarization. DNA was stained with DAPI (blue online). EP, epidermis; CRX, cortex. Bars = 20 μm (5 μm in insets).
The Caspase-Related Protease Separase (EXTRA SPINDLE POLES) Regulates Cell Polarity and Cytokinesis in Arabidopsis
Panagiotis N. Moschou, Andrei P. Smertenko, Elena A. Minina, Kazutake Fukada, Eugene I. Savenkov, Stephanie Robert, Patrick J. Hussey and Peter V. Bozhkov
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