At5PTase13 Modulates Cotyledon Vein Development through Regulating Auxin Homeostasis1[W]

Wen-Hui Lin, Yuan Wang, Bernd Mueller-Roeber, Charles A. Brearley, Zhi-Hong Xu, and Hong-Wei Xue*

National Key Laboratory of Plant Molecular Genetics, Institute of Plant Physiology and Ecology, Shanghai Institutes for Biological Sciences, Chinese Academy of Sciences, 200032 Shanghai, People’s Republic of China (W.-H.L., Y.W., Z.-H.X., H.-W.X.); Partner Group of the Max-Planck-Institute of Molecular Plant Physiology on Plant Molecular Physiology and Signal Transduction, 200032 Shanghai, People’s Republic of China (W.-H.L., Y.W., H.-W.X.); University of Potsdam, Institute of Biochemistry and Biology, D–14476 Golm, Germany (B.M.-R.); and School of Biological Sciences, University of East Anglia, Norwich NR4 7TJ, United Kingdom (C.A.B.)

Phosphatidylinositol signaling pathway and the relevant metabolites are known to be critical to the modulation of different aspects of plant growth, development, and stress responses. Inositol polyphosphate 5-phosphatase is a key enzyme involved in phosphatidylinositol metabolism and is encoded by an At5PTase gene family in Arabidopsis thaliana. A previous study shows that At5PTase11 mediates cotyledon vascular development probably through the regulation of intracellular calcium levels. In this study, we provide evidence that At5PTase13 modulates the development of cotyledon veins through its regulation of auxin homeostasis. A T-DNA insertional knockout mutant, At5pt13-1, showed a defect in development of the cotyledon vein, which was rescued completely by exogenous auxin and in part by brassinolide, a steroid hormone. Furthermore, the mutant had reduced auxin content and altered auxin accumulation in seedlings revealed by the DR5:β-glucuronidase fusion construct in seedlings. In addition, microarray analysis shows that the transcription of key genes responsible for auxin biosynthesis and transport was altered in At5pt13-1 seedlings. In addition, microarray analysis shows that the transcription of key genes responsible for auxin biosynthesis and transport was altered in At5pt13-1. The At5pt13-1 mutant was also less sensitive to auxin inhibition of root elongation. These results suggest that At5PTase13 regulates the homeostasis of auxin, a key hormone controlling vascular development in plants.

1 This work was supported by the Chinese Academy of Sciences and National Natural Science Foundation of China (grant nos. 30425029 and 30421001).

* Corresponding author; e-mail hwxue@sibs.ac.cn; fax 86–21–54924060.

The author responsible for distribution of materials integral to the findings presented in this article in accordance with the policy described in the Instructions for Authors (www.plantphysiol.org) is: Hong-Wei Xue (hwxue@sibs.ac.cn).

[W] The online version of this article contains Web-only data.

Article, publication date, and citation information can be found at www.plantphysiol.org/cgi/doi/10.1104/pp.105.067140.
required for the formation of continuous cotyledon secondary vein patterning.

Evidence suggests that auxin plays a critical role in the formation of cotyledon veins. The sfc mutants exhibit increased sensitivities to exogenous auxin (Deyholos et al., 2000), and auxin-resistant mutants, e.g. axr5 and axr6, show an incomplete vein pattern and defective development of vascular tissues (Hobbie et al., 2000). Studies employing polar auxin transport inhibitors indicate that the presence and polar transport of auxin are critical for vascular tissue development in cotyledons and leaves, especially the secondary and tertiary veins (Mattsson et al., 1999; Sieburth, 1999; Friml, 2003). Two different hypotheses have been proposed to explain how auxin is involved in vascular tissue development: (1) the auxin signal flow canalization hypothesis, based on experimental observation of the inductive effect of auxin on vascular tissue formation, and (2) the diffusion-reaction prepatter hypothesis, which is derived from computer modeling of interactions among hypothetical diffusible substances and positive feedback loops (Koizumi et al., 2000). However, the mechanism by which auxin modulates vascular development remains unclear. Furthermore, the mechanisms controlling auxin transport and accumulation during the cotyledon vein development are mysterious. Other phytohormones such as brassinosteroids (BRs) are also important for vascular development (Carland et al., 1999, 2002), but their mode of action and functional relationship to auxin are poorly understood.

The phosphatidylinositol (PI) signaling pathway participates in many developmental processes and cellular responses to environmental stimuli (Lin et al., 2004). Signaling molecules include phospholipids (PI phosphates) and soluble inositol phosphates. Inositol 1,4,5-trisphosphate [Ins(1,4,5)P3] (produced by phosphoinositide-specific phospholipase C-mediated hydrolysis of PI 4,5-bisphosphate) and inositol 1,3,4, 5-tetrakisphosphate [Ins(1,3,4,5)P4] play central roles in signal transduction. Both Ins(1,4,5)P3 and Ins(1,3,4,5)P4 regulate the release of internal Ca2+ stores and uptake of extracellular Ca2+ in animal cells (Zhu et al., 2000; Pouillon et al., 2003). Ins(1,3,4,5)P4 was excluded from the degradation products generated by endogenous phytase activity during phytate degradation assays (Hatzack et al., 2001). However, few reports have investigated the functions of Ins(1,3,4,5)P4 in higher plants.

Ins(1,3,4,5)P4 can be dephosphorylated by inositol phosphophosphate 1-phosphatase (IPP1ase; Xiong et al., 2001) or 5-phosphatase (5PTase; Berdy et al., 2001; Sanchez and Chua, 2001; Burnette et al., 2003; Zhong and Ye, 2004), both of which have been identified in plant cells. Phenotypic analyses of the relevant mutants indicated the involvement of IPP1ase in salt tolerance (Xiong et al., 2001), and the importance of 5PTase in abscisic acid (ABA) responses (Sanchez and Chua, 2001; Burnette et al., 2003) and cotyledon vein development (Carland and Nelson, 2004). Biochemical analyses showed that Arabidopsis 5PTases have phosphatase activity against different substrates including Ins(1,4,5)P3 and Ins(1,3,4,5)P4, phosphatidylinositol 4,5-bisphosphate, phosphatidylinositol 3,5-bisphosphate, and phosphatidylinositol 3,4,5-trisphosphate (Berdy et al., 2001; Ercetin and Gillaspy, 2004; Zhong et al., 2004; Zhong and Ye, 2004), similar to those in animal cells (Erneux et al., 1998). Different 5PTases have different substrate specificity, suggesting the presence of different types of 5PTases with distinct biological functions. Recent analysis revealed that cpv2 (with open vein networks and free vein endings) was due to a deficiency in At5PTase11 (Carland et al., 1999; Carland and Nelson, 2004), indicating that At5PTase11 and the PI signaling pathway are involved in vascular tissue development. Ins(3,4,5)P3 levels are elevated in the cpv2 mutant, suggesting a potential involvement of Ins(3,4,5)P3-mediated cytosolic calcium in the regulation of vascular development.

In this study, we demonstrate that an At5PTase knockout mutant exhibits a defect in cotyledon vein development and patterning, but this defect is distinct from that induced by cpv2 (At5PTase11) mutations. Furthermore, we show that this defect is rescued by exogenous auxin and that the At5PTase13 mutant has reduced auxin levels and altered expression of auxin-regulated genes. These results suggest that At5PTase has a function distinct from that of At5PTase11 and modulates vascular development through the regulation of auxin homeostasis.

RESULTS
Isolation of At5PTase13, an Arabidopsis Inositol Polyphosphate 5PTase Containing Multiple WD40 Repeats

An Arabidopsis cDNA (accession no. AC007153) was identified by homologously searching the National Center for Biotechnology Information database with a cDNA encoding a putative inositol polyphosphate phosphatase (AJ005682). Specific primers located in the predicted first exon were designed and used to screen an Arabidopsis hypocotyl cDNA library. We obtained an apparent full-length cDNA of 4,032 bp encoding a 1,094 amino acid polypeptide with a molecular mass of approximately 120 kD, named At5PTase13. Comparison of the cDNA with genomic sequences revealed the presence of 10 exons (80–800 bp) and nine introns (80–330 bp; Fig. 1A). The annotated gene structure in the database was essentially correct except for alterations in the sixth (one additional 104-bp intron was predicted) and final exons (the predicted exon is 227 bp longer). At5PTase13 is located on chromosome 1 (locus no. At1g05630) and presented in a single copy in the genome. During the manuscript preparation, Zhong et al. (2004) reported the molecular and biochemical characterization of At5PTase13, confirming its inositol polyphosphate phosphatase activity specifically toward Ins(1,4,5)P3.
At5PTase13 Is Expressed in Young Seedlings and Regulated by Phytohormones

Semiquantitative reverse transcription (RT)-PCR analysis revealed that At5PTase13 was expressed in young seedlings and flowers, while no transcripts were detectable in maturated roots, stems, and rosette leaves (Fig. 1B, left section). Further analysis via quantitative real-time RT-PCR confirmed the relatively higher expression of At5PTase13 in young seedlings and flowers, while lower expression in fruit, roots, stems, and leaves (right section). Data presented are compared with AtACTIN2 and shown as percentage. Bars indicate SD. C, Promoter-reporter (GUS) fusion studies demonstrate the At5PTase13 expression in the tips of cotyledons, root tip, and hypocotyl-root juncture at day 1 after germination, and then expand to the whole cotyledon. At days 3 and 5, the expression was concentrated at the pinnacle of cotyledons. Later (days 5–7, when the first two pairs of true leaves appeared), the expression of At5PTase13 decreased and was focused in cotyledon margin and root tip. At5PTase13 exhibited stronger expression in seedlings grown in darkness (middle section) and is also detected in inflorescence leaves, petals, and pollen grains, but weakly in sepal and rosette leaves (bottom section). Arrows show the positions of At5PTase13 expression. A few expression patterns are highlighted in rectangles. Bar = 1 mm. D, Semiquantitative RT-PCR analysis revealed that At5PTase13 was down-regulated following treatment with different plant hormones. Seven-day-old seedlings were treated with 100 μM auxin (IAA), cytokinin (Kinetin), GA (GA3), or 1 μM 24-eBL for 8 h.
while lower expression in fruits (Fig. 1B, right section). To further characterize At5PTase13 expression pattern, we fused the 1.4-kb At5PTase13 promoter region to the *Escherichia coli* β-glucuronidase (GUS) coding gene and transformed the resulting construct (pBI101-P) into Arabidopsis plants. T-DNA integration into the plant genome was confirmed by PCR analysis and five independent positive lines were identified (data not shown). In young seedlings, At5PTase13:GUS expression was detected in cotyledons prior to seed germination, and was expanded to root tips and juncture of hypocotyl. The maximal GUS expression of At5PTase13 was restricted to the cotyledon tips until 2 d after seed germination. On days 3 and 4, GUS was detected in the cotyledons or cotyledon veins. A similar pattern was detected on days 5 and 7, though the expression level was decreased. In addition, At5PTase13:GUS expression was observed at the cotyledon margins, juncture of hypocotyl and root, and root tips (Fig. 1C, top section). When the first pair of vegetative true leaves appeared around day 5, At5PTase13:GUS expression in cotyledons was reduced. Interestingly, the expression pattern of At5PTase13:GUS was very similar to auxin distribution in seedlings as indicated by a DR5:GUS expression (Fig. 3A).

At5PTase13:GUS activities were also detected in the apex of inflorescence (Fig. 1C, bottom section). At5PTase13:GUS was expressed in the hydratodes of inflorescence curling leaves, weakly expressed in sepal (relatively high in petal), and highly expressed in anther and pollen grains, but was not expressed in pistils.

Computational analysis of the At5PTase13 promoter region (http://www.dna.affrc.go.jp/htdocs/PLACE/signalscan.html) revealed the presence of potential cis-elements for auxin and blue light/UV responses, which is consistent with the observation that At5PTase13 expression was suppressed by auxin (Fig. 1D) and stimulated by darkness (Fig. 1C, middle section), especially in the hypocotyls on days 1 to 2 after germination. In addition, treatments of seedlings with plant hormones such as cytokinin, GA, and brassinolide (BL) suppressed At5PTase13 expression (Fig. 1D).

### At5PTase13 Deficiency Results in Abnormal Cotyledon Vein Development

To study the physiological role of At5PTase13, a putative T-DNA insertion line, Garlic 350-F1, termed as At5pt13-1, was identified using the At5PTase13 genomic sequence to search against the flanking sequence database of Arabidopsis mutant populations by Syngenta (Torrey Mesa Research Institute, Syngenta Research and Technology; the Syngenta Arabidopsis Insertion Library or SAIL, formerly known as GARLC). The putative insertion site was in the fourth exon of the At5PTase13 gene (Fig. 2A), which was confirmed by PCR amplification using primers located in the T-DNA (LB3) and flanking genomic regions (Fig. 2B, left).

Segregation ratio analysis of herbicide resistance (with a ratio of 3.04:1 of resistant:sensitive, in total 93 seedlings) and phenotypic observations (with a ratio of 1:1.94 of abnormal:normal seedlings, in total 53 seedlings) indicates the presence of a single T-DNA insertion, and that At5pt13-1 is a recessive mutation. Both heterozygous and homozygous plants were confirmed by PCR amplification using primers located in the T-DNA and flanking genomic regions (Fig. 2B, right). As expected, At5PTase13 transcript was not detected in the homozygous At5pt13-1 mutants (Fig. 2C).

According to the expression pattern of At5PTase13, we focused our observations on cotyledon development, especially the vascular tissues. There is no obvious growth difference between At5pt13-1 and wild-type seedlings, while the development of vascular tissues was obviously altered in At5pt13-1 (Table 1).

In wild-type plants, the primary vascular tissues of the cotyledons are clearly observed on day 2 after germination, and the secondary ones form 2 or 3 d later, with approximately symmetrical, continuous architectures and slick veins (Sieburth, 1999; Deyholos et al., 2000). Some proximal secondary veins do not close to the intending point in wild-type seedlings. A very low percentage (less than 1%) of the cotyledon veins is incomplete, anisomerous, or in incorrect orientation to the intending point in wild-type plants. Compared to wild-type plants (Fig. 2D, b), cotyledon veins of At5pt13-1 were with altered numbers (4%; Fig. 2D, b and c), in incorrect vein orientation (16.3%; Fig. 2D, d and e), with additional or altered loops (1.7%; Fig. 2D, f–h), with branches (1.3%; Fig. 2D, i and j), with intersections (1.3%; Fig. 2D, k) and fusions (5.3%; Fig. 2D, l) of the distal and proximal secondary veins, or with acute angles (3.3%; Fig. 2D, m). In addition, the cotyledon veins of At5pt13-1 were asymmetric, with flexed secondary veins and often multiple abnormalities, such as asymmetry, abnormal caecal orientation, or flex (10.7%). Statistical analyses revealed that around 64.7% of the total cotyledons showed obvious abnormality, while the ratio of seedlings with abnormal cotyledons reaches to approximately 90% (Table 1).

To investigate whether At5PTase is involved in the patterning of cotyledon veins or the differentiation of vascular cells, we examined the architecture and formation of cotyledon veins using differential interference contrast optics and cross sections. We found that the veins in the mutants, especially the secondary veins, were coarser than those in wild-type seedlings (Fig. 2D, o and q). However, the vascular cells did not show obvious cellular changes, suggesting At5PTase primarily modulates cotyledon vein patterning.

### At5PTase13 Could Complement the Abnormal Cotyledon Vein Development of At5pt13-1

To test whether the abnormal cotyledon vein patterns in At5pt13-1 are indeed due to the disruption of the At5PTase13 gene, a construct harboring At5PTase13 under its native promoter (pBI101-P-At5PTase13) was
transformed into wild-type and homozygous At5pt13-1. Four independent transgenic lines with single T-DNA insertion were identified. Semiquantitative RT-PCR analysis confirmed the rescued expression of At5PTase13 in these transformed At5pt13 lines (Fig. 2E), and further microscopic analysis indicated that the cotyledon veins of transgenic seedlings were normal in the T1 and T2 generation plants (Fig. 2D, r). Statistical analysis showed that the frequencies of abnormal cotyledon veins were significantly reduced in the transformed plants (Table I), indicating that abnormal cotyledon vein development of At5pt13-1 is due to the At5PTase13 deficiency.

Exogenous Auxin and BL Rescue the Abnormal Cotyledon Vein Development in At5pt13-1

Both auxin and BRs are known to regulate the development of both leaf and cotyledon veins (Semiarti et al., 2001). We thus tested whether the abnormal cotyledon veins of At5pt13-1 could be rescued by exogenous auxin or BR. Interestingly, the abnormal cotyledon veins were almost completely rescued by low concentrations of naphthylacetic acid (NAA; 0.1 μM; Fig. 2D, s and t) or in part by 24-epi-BL (24-eBL; 0.1 μM). Statistical analyses indicated that the frequency of NAA-treated or 24-eBL-treated At5pt13-1 with abnormal cotyledon veins was reduced, i.e. from 90% to 15% and 39%, respectively (Table I). These results suggest that At5PTase13 is involved in the accumulation and distribution required for normal vascular patterning.

We next examined whether the At5pt13-1 mutation alters the distribution and the level of auxin. Arabidopsis plants harboring DR5:GUS construct (Ulmasov et al., 1997) were employed, and a homozygous line of DR5:GUS and At5pt13-1 was obtained by crossing. As shown in Figure 3A, At5pt13-1 dramatically altered both the distribution and the level of DR5:GUS expression (Fig. 3B). These results suggest that At5PTase13 is involved in the accumulation and distribution required for normal vascular patterning.
expression. GUS levels were reduced throughout the whole seedlings, especially in cotyledons at 1 to 2 d after germination, and the distribution was modified in root tissues (absent in the root tip but dispersed in the elongation zone). In 4-d-old seedlings, the GUS level in crossed offspring is much reduced compared to that in the controls. When exogenous auxin (NAA, 0.1 μM) was applied to DR5:GUS/AT5PT13-1 seedlings, GUS levels and distribution was recovered nearly to those in wild-type background, although the GUS levels were still relatively lower compared to wild type, especially at 4 d after germination (Fig. 3A).
To assess whether the At5pt13-1 indeed affected free auxin levels, we assayed free auxin using an ELISA method as described (Liang and Yin, 1994). As shown in Figure 3B, the auxin content in 4-d-old At5pt13-1 seedlings is approximately half of that in wild-type ones, confirming that At5PTase13 modulates auxin accumulation.

**Auxin Biosynthesis and Transport-Related Genes Are Modified in At5pt13**

To explore the possible mechanism for At5PTase13 regulation of auxin accumulation and distribution, we examined whether At5PTase13 affected the expression of auxin biosynthesis- and transport-related genes. Semiquantitative RT-PCR analysis shows that out of five auxin biosynthesis-related genes covering three different biosynthesis pathways (Bartel et al., 2001) and six transport-related genes (PIN1–4, 6, and 7; Friml, 2003), two showed modified transcript levels in At5pt13-1 (Fig. 4A, top section). Real-time quantitative PCR analysis confirmed the unaltered expression of NIT1 (Nitrilase 1; while NIT3 was enhanced; Table II) and stimulated expression of CYP83B1 and PIN4 (Fig. 4A, bottom section). Transcript level of CYP83B1, acting as an important branch point for auxin and glucosinolate biosynthesis, was increased in At5pt13-1 (4-d-old seedlings). A loss-of-function mutant of CYP83B1 (sur2) was previously reported to have a higher level of free auxin and a reduced glucosinolate level, while a transgenic line overexpressing CYP83B1 had low auxin and high glucosinolate levels (Bak et al., 2001; Bartel et al., 2001). This is consistent with our observation that the amount of auxin is reduced in At5pt13-1. The increased expression of PIN4, which is responsible for maintaining the auxin gradient in roots and helps to initiate or stabilize an auxin feedback loop (Friml, 2003), suggests that auxin transport is also modified in At5pt13-1 mutant plants, consistent with their altered auxin distribution.

To further investigate the possible mechanism of At5PTase13 action and to confirm the altered expression of auxin-related genes in the At5pt13-1 mutant, we performed a global gene expression profiling of the 4-d-old aerial organs of wild-type and At5pt13-1 seedlings using the whole-genome microarray chip (Affymetrix, ATH1). The hybridization results revealed altered expression of auxin biosynthesis- and signaling-related genes (Tables II and III). Under the At5PTase13 deficiency, the expression of genes encoding proteins involved in auxin biosynthesis, especially those related to the Trp-dependant pathway and the indole glucosinolate branch (Bartel et al., 2001), was differentially modified. Among them, expression of AAO1 (indole-3-acetaldehyde oxidase) and CYP83B1 (cytochrome P450) was enhanced, while the expression of NIT3, TRP2 (Trp synthase β), and TRP3 (Trp synthase α) was suppressed (see Fig. 4B). In addition, about 30 auxin-related genes, coding for auxin-induced proteins or auxin-responsive factors, were affected (Table III). It was interesting to note that the BR biosynthesis-related genes were not modified in the At5pt13-1 mutant except for DWF4, whose expression was slightly suppressed. Genes involved in cytokinin and GA metabolism were also affected, consistent with the RT-PCR analysis showing that cytokinin and GA suppress At5PTase13 transcription. In addition to the hormone-related genes, genes encoding proteins participating in signal transduction (10% of the total regulated genes), transcription (8%), disease resistance (2%), metabolism (17%), photomorphogenesis (1%), and development (1%) exhibited altered expression in At5pt13-1 (Supplemental Table I). Taken together, these results suggest the involvement of At5PTase13 in multiple growth and developmental processes and responses to the environment.

**At5pt13-1 Is Less Sensitive to Auxin and ABA**

We also tested whether At5pt13-1 altered auxin sensitivity. Root lengths of At5pt13-1 seedlings on the medium supplemented with different concentrations of auxin (indole-3-acetic acid [IAA], 0.01, 0.1, 1, and 10 μM) were measured and the relative promotion and inhibition were calculated. The results show that, compared to the wild-type seedlings, At5pt13-1 is less sensitive to exogenous IAA, especially at concentrations of 0.01, 0.1, and 1 μM (Fig. 5A). Microarray analysis described above indeed showed that auxin-related genes, including genes coding for auxin-regulated proteins and auxin-responsive factor-like...
Figure 3. Altered auxin accumulation and distribution in At5PTase13-deficient plants. A, GUS activity detection of homozygous DR5:GUS/At5pt13-1 cross offsprings implies altered auxin levels and distribution in At5pt13-1 seedlings grown at 1, 2, and 4 d (two independent homozygous lines, L1 and 2) after germination. Adscititious NAA in low concentrations could enhance auxin levels in both DR5:GUS/At5pt13-1 and control plants. Bar = 4 mm. B, Quantitative assay of free auxin content in wild-type and At5pt13-1 seedlings. Four-day-old seedlings were used for ELISA analysis. The measurements were repeated four times and bars indicate SD.
protein (ARF6, 9), are differentially regulated (Table III). These results support the involvement of At5PTase13 in auxin signal transduction as well.

Previous studies showed that overexpressed At5PTase13 resulted in the insensitivity of transgenic plants to exogenous ABA (Sanchez and Chua, 2001). In contrast, fry1 and cvp2, which were deficient in AtIPPIase and At5PTase11, respectively, were hypersensitive to exogenous ABA, consistent with increased Ins(1,4,5)P_3 levels (Xiong et al., 2001; Carland et al., 2001).

Figure 4. The At5pt13 knockout mutation alters the expression of auxin biosynthesis- and transport-related genes. A, Semiquantitative RT-PCR analysis indicates increased expression of CYP83B1 and PIN4 in At5pt13-1. RNA was extracted from 4-d-old seedlings and PCR amplifications were performed using Arabidopsis actin or tubulin (locus nos. At3g18780 and At5g62690), respectively, as internal positive controls (bottom section). Further analysis via quantitative real-time RT-PCR confirmed the unaltered expression of NIT1 and stimulated expression of CYP83B1 and PIN4 (bottom section). Data presented are compared with AtACTIN2 and shown as percentage of the AtACTIN2 expression. Bars indicate SD. B, Summary of the genes involved in auxin homeostasis with altered transcripts by microarray analysis. TRP3, TRP2, and NIT3 were suppressed, and CYP83B1 and AAO1 were enhanced, under At5PTase13 deficiency. C, The hypothesized model of how At5PTase13 is involved in the cotyledon vein development through regulating auxin homeostasis and Ins(1,3,4,5)P_4-related Ca^{2+}. In normal conditions, At5PTase13 suppresses CYP83B1 and keeps higher IAA/indole-3-acetonitrile (IAN) homeostasis. In At5pt13-1, release of CYP83B1 leads to more IAN in vivo and lower IAA/IAN homeostasis. Ins(1,3,4,5)P_4-related Ca^{2+} may interact with auxin homeostasis to modulate the vascular development.
and Nelson, 2004). To explore whether At5pt13-1 has similar phenotypes, relevant experiments were performed, and our results showed that, in contrast to fry1 and cvp2, At5pt13-1 was insensitive to exogenous ABA. As shown in Figure 5B, on the medium containing 1 or 3 μM ABA, At5pt13-1 had much improved seed germination over the 6-d period (76% versus 31% with supplemented 3 μM ABA) compared to wild-type seeds. These results further confirm that At5PTase13 is functionally distinct from At5PTase11.

DISCUSSION

It is known that auxin and its polar transport is required for vascular differentiation and patterning in cotyledons and leaves, but the mechanisms controlling auxin accumulation and polar transport during these processes are not understood. In this study, we provide evidence that At5PTase13, a key enzyme in the PI signaling pathway, is required for normal vein formation in the cotyledon through the regulation of auxin homeostasis (probably auxin accumulation and polar transport)
Our data suggest that At5PTase13 appears to act in a pathway distinct from that mediated by At5PTase11, which is encoded by the CVP2 gene that has been shown to be involved in cotyledon vein patterning in Arabidopsis (Carland et al., 1999, 2002). At5PTase13 belongs to a plant-specific subfamily of 5PTases (Zhong and Ye, 2004). Members of this group of 5PTases contain a Trp-Asp signature (WD40 repeats), suggesting their participation in signal transduction. WD40 repeats have been shown to exist in a number of proteins, such as yeast (Saccharomyces cerevisiae) TUP1 (thymidine uptake 1; 5 repeats) and STE4 (a G-β-like protein; 8 repeats; Williams and Trumbly, 1990; Grotewold et al., 1991), and Arabidopsis proteins COP1 (a repressor of photomorphogenesis), SPA1 (suppressor of phyA-105), and TGG1 (transparent testa glabra 1; Hoecker et al., 1999; Osterlund et al., 1999; Walker et al., 1999). The WD40 domain present in COP1 interacts with transcription factors HY5 (long hypocotyl 5) and HYH (HY5 homolog), both of which are involved in light-dependent gene expression, specifically photomorphogenesis (Holm et al., 2001, 2002) and proteasome-mediated degradation (Suzuki et al., 2002). The function of the WD40 domain in At5PTase proteins is still unknown, but its presence may provide a means of protein-protein or protein-DNA interactions between At5PTase and other undefined cellular components. In addition, the presence of the WD40 domain in plant but not animal 5PTases, suggests a unique regulatory mechanism for these plant-specific 5PTases and/or their unique physiological roles in plants.

The distinction of the At5PTase13 structure from that of At5PTase11/CVP2, which lacks the WD40 domain, is consistent with the functional differences between these two 5PTases, although they both participate in vascular development. Interestingly, At5pt13-1 and cvp2 mutants showed opposite responses to ABA. Previous studies showed that deficiency of At5PTase1 and CVP2 resulted in the ABA hypersensitivity associated with increased Ins(1,4,5)P3 levels. However, At5pt13-1 showed reduced ABA sensitivity (Fig. 5, B and C). The distinct function from these two 5PTases could be explained by the differences in their substrate specificities. At5PTase11 has been shown to dephosphorylate Ins(1,4,5)P3, thus its mutation leads to increased sensitivity to ABA. These results suggest that At5PTase13 may play a role in ABA signaling in Arabidopsis.

**Figure 5.** At5pt13-1 is less sensitive to auxin and ABA. A, Lengths of the primary roots of 7-d-old wild-type and At5pt13-1 seedlings on the medium supplemented with gradient auxin (0, 0.01, 0.1, 1, or 10 μM) were measured and the relative ratios of growth promoting and restraining were calculated. Error bars indicate SD, and the asterisk indicates the significant difference (P < 0.01) by one-tailed Student's t-test. B, Seed germination for both wild type and At5pt13-1 was assayed on the medium supplemented with 1 μM (top section) or 3 μM ABA (bottom section) over a 6-d period. Error bars indicate SD. C, ABA dosage effects on seed germination for both wild type and At5pt13-1. Squares, At5pt13-1; circles, wild type. Error bars indicate SD. D, Semiquantitative RT-PCR analysis indicates no changes in CVP2 transcript levels in At5pt13-1. RNA was extracted from 4-d-old seedlings and PCR amplifications were performed for 36 cycles using tubulin (locus no. At5g62690) as internal positive control.
accumulation of this second messenger that presumably mobilizes the release of intracellular Ca$^{2+}$ stores. In contrast, At5PTase13 could primarily dephosphorylate Ins(1,3,4,5)P$_4$. It was shown that Ins(1,3,4,5)P$_4$ was responsible for calcium extracellular circulation and thus affects intracellular Ca$^{2+}$ levels (Mishra and Delivoria-Papadopoulos, 2004).

Expression pattern analysis revealed the expression of At5PTase13 in young seedlings, especially cotyledons, similar to the study of Zhong and Ye (2004). Genetic analysis employing a knockout mutant, At5pt13-1, revealed the abnormal development of cotyledon veins. An important role of At5PTase13 and hence, inositol polyphosphate in cotyledon vein development, was further confirmed by treatment of wild-type plants with exogenous Ins(1,3,4,5)P$_4$ (0.01 μM; Table 1), suggesting that the accumulation of the potential At5PTase13 substrate, Ins(1,3,4,5)P$_4$, could at least in part lead to altered cotyledon vein patterns. The occurrence of abnormal cotyledon veins that could be rescued by low concentrations of BRs or NAA (two phytohormones essential for cotyledon vein development) indicates that At5PTase13 is involved in hormone-related cotyledon vein pattern formation. Indeed, previous studies have indicated that auxin is critical for cotyledon vein development. Deficiency of the SHY2 gene, which encodes IAA3, a light-regulated member of the auxin-induced auxin/IAA multigene family, leads to vascular tissue deficiencies (Tian et al., 2002). Altered expression of many auxin-induced genes in this mutant indicates that SHY2/IAA3 is likely a negative factor of auxin signaling and mostly affects the primary action of auxin (Tian et al., 2002). We show that At5pt13-1 exhibited enhanced expression of CYP83B1 and PIN4. CYP83B1 has been shown to decrease the level of IAA by distributing indole-3-acetaldoxime to the glucosinolate pathway, and previous studies showed that CYP83B1-deficient plants overaccumulated IAA, indole-3-acetaldehyde, and IAA-Asp, whereas CYP83B1 overexpression resulted in high indole glucosinolates and low IAA (Bartel et al., 2001). These observations are consistent with the decreased auxin contents observed in At5pt13-1 and at least in part explain how exogenous supplemented auxin rescues the abnormalities. Regarding auxin transport, PIN4-dependent auxin transport actively maintains the auxin gradient in roots, stabilizing it through a feedback loop (Friml, 2003). The increased expression of PIN4 in At5pt13-1 is consistent with our observation that the distribution of auxin in roots, hypocotyls, and cotyledons was altered in At5pt13-1. In addition to its effect on auxin distribution and accumulation, At5PTase appears to modulate auxin signaling as well, as suggested by reduced sensitivity of At5pt13-1 to exogenous auxin and altered transcription of auxin-related genes, including those coding for auxin-induced proteins and auxin-responsive factors in this mutant.

It was suggested that CVP2 regulates cotyledon vascular development by an Ins(1,4,5)P$_3$ and Ca$^{2+}$-dependent pathway (Carland and Nelson, 2004). Furthermore, the fact that exogenous auxin could not rescue cvp2 phenotype suggests that CVP2 mediates this process through an auxin-independent pathway. The defect in cotyledon vein patterning in At5pt13-1 could be restored by auxin and could be mimicked by exogenous Ins(1,3,4,5)P$_4$, implying the involvement of At5PTase13 in both Ca$^{2+}$- and auxin-dependent vascular development. Further studies will be necessary to test this hypothesis.

In conclusion, we have demonstrated that AtPTase13 modulates cotyledon vein patterning via the regulation of auxin homeostasis, a mechanism that is distinct from the one that underlies AtPTase11/CVP2 modulation of cotyledon vein development. Arabidopsis contains a multigene family of 5PTases (Berdy et al., 2001; Ercetin and Gillaspy, 2004; Zhong et al., 2004). Our analysis showed that in addition to At5PTase13, five other AtPTase genes are transcribed in cotyledons (W.-H. Lin and H.-W. Xue, unpublished data). An interesting question is whether these At5PTases are also involved in the regulation of vascular development. In the future, detailed studies on the expression patterns of the various 5Tase genes, their knockout phenotypes, and their substrate specificities will provide insights into this question.

**MATERIALS AND METHODS**

**Enzymes and Compounds**

Enzymes used for DNA manipulation were purchased from Boehringer Mannheim and New England Biolabs. DNA primers used for PCR were obtained from TibMolbiol. d-myo-inositol 1,3,4,5-tetrakisphosphate (sodium) was obtained from Echelon.

**Bacteria and Plants**

*Escherichia coli* strain XL-1 Blue (Stratagene) was used for DNA cloning and library screening. Arabidopsis (*Arabidopsis thaliana*) L. Heglu (Columbia ecotype) seeds were surface sterilized with 20% bleach and washed four times with sterile water, then germinated on agar medium containing half-strength Murashige and Skoog salts. Plants were then placed in soil and grown in a phytofon with a 16-h-light (22°C) and 8-h-dark (18°C) cycle. For phytohormone treatments, 7-d-old seedlings were treated with 100 μM auxin (IAA), 100 μM cytokinin (Kinetin), 100 μM GA (GA3), or 1 μM 24-EBL for 8 h. Exogenous 0.1 μM NAA (Sigma) or 0.1 μM 24-EBL (Sigma) were used for supplementing phytohormones during seedling growth. Plant crosses were carried out by removal of the petals, sepals, and androecia from large green buds and subsequent artificial fertilization at 12 h to 3 m over the next 2 d. Arabidopsis plants were transformed by floral dipping into *Agrobacterium tumefaciens* GV3101 strains containing binary vectors. For the seed germination assay, 50 seeds from wild-type and At5pt13-1 plants were sown on Murashige and Skoog medium containing different concentrations of ABA (0, 1, 2, and 3 μM). Seeds were regarded as germinated when radicle completely penetrated the seed coat, and germination was scored daily up to 6 d after being placed at room temperature. For the seedling hormone sensitivity assay, lengths of primary roots of 7-d-old wild-type and At5pt13 seedlings on the medium supplemented with gradient auxin (0, 0.01, 0.1, 1, or 10 μM) were measured, and the relative ratios of growth promoting and restraining were calculated. The experiments were repeated in duplicates.

**Isolation of At5PTase13 cDNA**

DNA manipulation was performed using standard protocols (Sambrook et al., 1989). The cDNA sequence coding for an inositol polyphosphate 5Tase (AJ005682; H.-W. Xue, unpublished data) was used as probe to search against...
the National Center for Biotechnology Information database (http://www.ncbi.nlm.nih.gov/ dbEST/index.html), resulting in the identification of a putative inositol polyphosphate 5′Pase coding region from Arabidopsis (accession no. AC007153). Specific primers located in the predicted first exon (AT5Pt-1, 5′-CGGAAGGAGACGAGGACC-3′ and AT5Pt-2, 5′-CGGAAGGAGACGAGGACC-3′) were designed and used for PCR amplification. The resulting PCR product was used to isolate the corresponding cDNAs from an Arabidopsis hypoxyl cDNA library via a PCR-based strategy (Allanandari and Darribere, 1994), and plaque-purified phage clones were converted to pBluescript derivatives using ExAssist helper phage according to the suppliers instructions (Stratagene). The clone containing the longest cDNA insert (pAT5Pt13) was used for further analysis. DNA sequencing was performed by Genecore and computational analysis was based on the programs of the Wisconsin Genetics Computer Group (GCC package, version 10.1).

Semiquantitative RT-PCR Analysis and Promoter-Reporter Gene Fusion Studies

Semiquantitative RT-PCR was used to study the mRNA expression of At5Ptase13 in various tissues. Total RNAs from 4-d-old seedlings, cotyledons, 3-week-old rosette leaves, roots, flowers, and stems after 1 week flowering and 3-week-old rosette leaves, roots, flowers, and stems after 1 week flowering and homozygous lines and were confirmed through PCR amplification with Arabidopsis actin-coding cDNA (gene locus no. At1g09240) used as an internal positive control with primers Act-a1 (5′-GCAGTTTCTCCAGGATGTTG-3′) and Act-b1 (5′-TTCGCTGACCTCTCATTAC-3′). PCR reactions were as follows: 94°C for 2 min; followed by 32 or 36 cycles of 94°C for 1 min, 56°C for 45 s, and 72°C for 1 min, with a final extension at 72°C for 10 min. The resulting PCR products were resolved on 1% to 2% agarose gels and assessed using a Gel Doc 2000 system (Bio-Rad).

The expression pattern of At5Ptase13 was further analyzed using transgenic expression of the promoter-reporter gene fusion. A 1.4-kb genomic DNA region in front of the translation initiation site ATG was analyzed for the presence of cis-regulatory elements, and then PCR amplified with primers At5Pt13pro-1 (5′-TTGATGTGTACTATGATTATCATC-3′) and At5Pt13pro-2 (5′-GCAGAATTCAGGAGATCAG-3′). The amplified DNA fragment was confirmed by sequencing and then subcloned into pBI101 vector (General Biomass) to yield the construct harboring this region fused to a reporter gene (E. coli GLS). This construct (pBI101-P) was transformed into Arabidopsis. Transgenic seedlings were screened on Murashige and Skoog medium supplemented with 30 mg/L kanamycin, and T-DNA integration was confirmed by PCR analysis using primers annealing to the kanamycin resistance gene (NPTII-s, 5′-GGAATATCATAGCC-3′) and NPTII-a, 5′-ATGGCCATCATGCAAGAT-3′; 1-2, 3-, 5-, and 7-old of seedlings from two homozygous plants were analyzed for GUS activities as described by Jefferson et al. (1987), with an SMZ 800 stereo scope (Nikon).

Identification of an At5Ptase13 Knockout Mutant

The At5Ptase13 genomic sequence was used to BLAST search the flanking sequences database of the Arabidopsis mutation populations offered by Syngenta (http://www.syngenta.com), resulting in the identification of an insertion line, Garlic 330-F1. Mutant seeds were screened in one-half Murashige and Skoog medium containing 20 mg/L Basta for calculating the segregation ratio and homozygous lines and were confirmed through PCR amplification with primers At5Pt3con-1 (5′-CGGGATCCCAAGGAACTACTATGAC-3′) and At5Pt3con-2 (5′-TACGATACCATGCTCAACAT-3′) in combination with the T-DNA specific primer (LB3).

To confirm the At5Ptase13 deficiency, total RNA was extracted from 4-d-old mutant and wild-type seedlings, reverse transcribed, and used as templates for RT-PCR analyses using primers At5Pt13dei-1 (5′-AAGGCGATTTCTTGCGTGGTGTC-3′) and At5Pt13dei-2 (5′-TCCCTTGTTTATGCTCTGGTGTC-3′). The experiments were repeated three times with independent samples. The knockout mutant was designated as At5pt13-I.

Phenotypic Analysis of At5pt13-I

Cotyledon veins of 2-, 4-, and 6-d-old At5pt13-I mutant and wild-type seedlings were observed. The cotyledons were cleared in 95% ethanol to remove chlorophyll and fixed with formaldehyde-acetic acid buffer (30% ethanol, 5% acetic acid, 3.7% formaldehyde, and 41.3% water) for at least 15 min. Before observation using an SMZ 800 stereo scope, the materials were treated overnight with HCG clearing solution (Sabatini et al., 1999). Structures of the cotyledon veins were observed using differential interference contrast optics (Leica DMR microscope equipped with a Leica DC 300F digital camera). The numbers of cotyledons with abnormal veins were counted and ratios (the percentage of cotyledons with abnormal veins of the total observed cotyle- dons) were calculated.

Complementation of the At5pt13-I Mutant

The full-length At5Ptase13 cDNA was subcloned into construct pH101-P prext with Xhol and Sall, and the resulting construct containing At5Ptase13 cDNA under its own native promoter (pBI101-P-At5Ptase13) was transformed into wild-type and homozygous mutant plants. The T0 seeds were screened on medium containing 30 mg/L kanamycin and the resistant plants were confirmed to be transgenics by PCR amplification using primers annealing to the kanamy cine resistance gene (NPTII-s and NPTII-a). The rescued expression of At5Ptase13 in mutant plants was confirmed through semiquantitative RT-PCR using primers At5Pt13dei-1 and -2. The cotyledons were dissolved by 95% ethanol and fixed by formaldehyde-acetic acid, and then observed.

Measurement of Auxin Content in Seedlings

To measure auxin contents, 4-d-old wild-type and At5pt13 seedlings were sampled with a mortar and pestle, and similar amounts of samples (300 mg of fresh weight) were used for the measurement of IAA contents. IAA was extracted by 80% methanol and centrifugated at 5,000g for 10 min at 4°C. The supernatant was collected and immediately applied to a pre-equilibrated C18 Sep-Pak cartridge (Millipore), which was washed with 70% methanol solu- tion. After methyl-esterification with diazomethane, the free IAA content was measured by ELISA (as described by Liang and Yin, 1994). In detail, 96-well immunomass plates were coated with mouse anti-IAA monoclonal antibody (0.1 mL, 1:10,000) in 50 mM NaHCO3 (pH 9.6) at 37°C overnight with 100% humidity. Standard curve was generated under different concentrations of IAA standard buffer (1,000, 250, 62.5, 15.63, 3.9, and 0.98 pmol/50 mL). After incubation, the supernatant was discarded and the plates were washed twice (phosphoric buffer) and then incubated with Oulabumin at 37°C for 30 min. After further wash and dispensation of IAA standard buffers, the plates were incubated with horseradish peroxidase-linked rabbit anti-mouse (1:20,000) in 50 mM NaHCO3 (pH 9.6) at 37°C for 70 min. The conjugate was removed by washing and optical densities were measured at 490 nm.

Semiquantitative RT-PCR Analysis of mRNA Expression of Auxin Biosynthesis- and Transport-Related Genes

Expression of genes encoding auxin biosynthesis- and transport-related proteins in At5pt13 plants was analyzed using semiquantitative RT-PCR. The selected genes and the relevant primer sequences were as follows: FMO/ YUCCA (flavin-containing monoxygenase, At4g32540, YUCCA-s, 5′-AACA- CGGCCATCCATATGCGC-3′, and YUCCA-a, 5′-AAGGCAAATGAGGATCCTC-3′); CYP79B (cytochrome P450 family member, At1g05090, CYP79B-s, 5′-CGGGTCTTCGTACGATTGTC-3′, and CYP79B-a, 5′-TCTGTCACCAC- GCTTC-3′); CYP81B1 (cytochrome P450 monoxygenase, At4g3100, CYP81B1-s, 5′-AAGGCGATTTCTTGCGTGGTGTC-3′ and CYP81B1-a, 5′-TTCGGCTATCCATGAC-3′); PIN1 (At5g4310, PIN1-s, 5′-TCTGGTTTGCCCTGTTTACCCAG-3′); PIN2 (At5g4310, PIN2-s, 5′-TACGAGGATTGCTGAC-3′); PIN3 (At5g4310, PIN3-s, 5′-TCTGGTTTGCCCTGTTTACCCAG-3′); PIN4 (At5g4310, PIN4-s, 5′-TACGAGGATTGCTGAC-3′); PIN5 (At5g4310, PIN5-s, 5′-TACGAGGATTGCTGAC-3′); PIN6 (At5g4310, PIN6-s, 5′-TACGAGGATTGCTGAC-3′); PIN7 (At5g4310, PIN7-s, 5′-TACGAGGATTGCTGAC-3′) and PIN8 (At5g4310, PIN8-s, 5′-TACGAGGATTGCTGAC-3′); AtPIN1 (At1g06360, AtPIN1-s, 5′-TCTGGATTCATGTCGGTC-3′) and AtPIN2 (At1g06360, AtPIN2-s, 5′-TCTGGATTCATGTCGGTC-3′); AtPIN3 (At1g06360, AtPIN3-s, 5′-TCTGGATTCATGTCGGTC-3′); AtPIN4 (At1g06360, AtPIN4-s, 5′-TCTGGATTCATGTCGGTC-3′); AtPIN5 (At1g06360, AtPIN5-s, 5′-TCTGGATTCATGTCGGTC-3′); AtPIN6 (At1g06360, AtPIN6-s, 5′-TCTGGATTCATGTCGGTC-3′); AtPIN7 (At1g06360, AtPIN7-s, 5′-TCTGGATTCATGTCGGTC-3′); AtPIN8 (At1g06360, AtPIN8-s, 5′-TCTGGATTCATGTCGGTC-3′).
Real-Time Quantitative RT-PCR Analysis

Quantitative RT-PCR analyses were performed to study the transcription levels of At5pt13 at three different stages (with primers RT1s, 5'-GTTTAGGCTAGTGTGAGTGTCTCT-3' and RT2s, 5'-ATGGCGATAGTTGCTGCTT-3'). The RT-PCR was performed and Arabidopsis actin2 encoding gene (locus no. At3g18780) was used as internal control.

Expression Profiling of Genes in At5pt13-1 Seedlings Using Microarray Analysis

Shoots of 4-d-old At5pt13-1 and wild-type plants were harvested and RNA samples were prepared according to the protocols by manufacturers (Affymetrix). Briefly, total RNA was extracted and 2 μg of poly(A)-stained RNA was converted to double-stranded cDNA using the SuperScript polymerase II (Affymetrix) protocol. A total of 3- to 300-bases pieces of fragmented RNA was hybridized with an Arabidopsis genome array (Affymetrix ATH1).

Accession Numbers

Nucleotide sequences reported in this paper have been submitted to the GenBank/EMBL Data Bank under accession numbers A1827426 (At5pt13), NM_112764 (Actin2), and M20405 (β-tubulin2).

ACKNOWLEDGMENT

We greatly thank Mr. Jan Xu (Utrecht University, The Netherlands) for providing the Arabidopsis seeds containing the DR5-GUS construct.

REFERENCES


Lin et al.


Copyright © 2005 American Society of Plant Biologists. All rights reserved.


