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AtDsPTP1 acts as a negative regulator in osmotic stress signalling during Arabidopsis seed germination and seedling establishment

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Abstract

Dual-specificity protein phosphatases (DsPTPs) target both tyrosine and serine/threonine residues and play roles in plant growth and development. We have characterized an Arabidopsis mutant, dsptp1, which shows a higher seed germination rate and better root elongation under osmotic stress than the wild type. By contrast, its overexpression line, DsPTP1-OE, shows inhibited seed germination and root elongation; and its complemented line, DsPTP1-Com, resembles the wild type and rescues DsPTP1-OE under osmotic stress. Expression of AtDsPTP1 is enhanced by osmotic stress in seed coats, bases of rosette leaves, and roots. Compared with the wild type, the dsptp1 mutant shows increased proline accumulation, reduced malondialdehyde (MDA) content and ion leakage, and enhanced antioxidant enzyme activity in response to osmotic stress. AtDsPTP1 regulates the transcript levels of various dehydration-responsive genes under osmotic stress. Abscisic acid (ABA) accumulation in dsptp1 under osmotic stress is reduced with reduced expression of the ABA-biosynthesis gene NCED3 and increased expression of the ABA-catabolism gene CYP707A4. AtDsPTP1 also regulates the expression of key components in the ABA-signalling pathway. In conclusion, AtDsPTP1 regulates ABA accumulation, and acts as a negative regulator in osmotic stress signalling during Arabidopsis seed germination and seedling establishment.

Key words: Abscisic acid (ABA), Arabidopsis, dual-specificity protein phosphatase, osmotic stress, root elongation, seed germination.

Introduction

The signalling pathways of plants under osmotic stress have been intensively studied during the past two decades (Hasegawa et al., 2000; Xiong et al., 2002; Xiong and Zhu, 2002; Fujii and Zhu, 2012). Different protein kinases and transcription factors reportedly minimize damage caused by osmotic stress (Droillard et al., 2004; Gilmour et al., 2004).
Abscisic acid (ABA) synthesis is significantly induced by the stress and its signalling has a crucial function in abiotic stresses responses (Agarwal and Jha, 2010; Fujita et al., 2011). The core module of the ABA-signalling pathway in response to osmotic stress, as well as other abiotic stresses, has been elucidated (Ye et al., 2012). However, many components in the signalling network of osmotic stress remain unknown (Cutler et al., 2010). Further analysis is needed to determine the exact functions and connections among the components involved in the regulation of plant responses to osmotic stress.

Similar to protein kinases, protein phosphatases (PPs) are also indispensable in stress signalling. According to their dephosphorylation targets, PPs can be divided into two groups, namely serine/threonine phosphatases and protein tyrosine phosphatases (PTPs), both of which have key functions in plant growth regulation and abiotic stresses responses (Schweighofer et al., 2004; Schweighofer and Meskiene, 2008; Bartels et al., 2010). Dual-specificity protein phosphatases (DsPTPs) can target both tyrosine and serine/threonine (Keyse, 1995). Except for the active site motif, DsPTPs do not share sequence similarity with PTPs. DsPTPs often have strict substrate specificity, and each member usually acts on only one or a limited number of target proteins (Keyse, 1995). In Arabidopsis, different DsPTPs and their associated protein kinases control plant growth and development under stress conditions. For example, mutation of the MKP1 gene results in plant hypersensitivity to stresses imposed by ultraviolet light and methyl methanesulfonate (Ulm et al., 2001). By contrast, mKP1 plants show hyposensitivity to salt stress (Ulm et al., 2002). PHS1, a DsPTP, controls microtubule organization and embryonic development (Naoi and Hashimoto, 2004). Furthermore, AtPTEN1, which encodes another DsPTP, is expressed exclusively in pollen and is essential for pollen development (Gupta et al., 2002). These studies suggest that DsPTPs have diverse functions in different biological processes.

Increasing evidence has shown that many protein kinases have positive functions in the osmotic stress-signalling pathway (Fujii and Zhu, 2012). However, PPs are also involved in the signalling process. In alfalfa, MP2C, a PP2C, suppresses the lethal phenotype induced by STE11, which is involved in the hyperosmotic HOG1 cascade (Meskiene et al., 1998). Furthermore, MP2C phosphatophosphorylates and inactivates the stress-activated SIMK (Meskiene et al., 2003). In Arabidopsis, AtDsPTP1 dephosphorylates AtMAPK4 and AtMAPK6 in vitro, leading to the inactivation of these kinases that participate in osmotic stress signalling (Huang et al., 2000; Gupta and Luan, 2003). Two Arabidopsis PP2Ccs, ABI1 and ABI2, negatively regulate ABA signalling in drought-induced stomatal closure (Schweighofer et al., 2004). However, the function of DsPTPs in osmoregulation is still unknown. One report on the identification of the mKP1 mutant, which exhibits enhanced salt stress tolerance, indicates that the DsPTPs have critical functions in osmoregulation (Droillard et al., 2004). Investigation of the functions of AtDsPTPs in response to osmotic stress is of great significance.

The AtDsPTP1 gene of Arabidopsis was identified more than a decade ago. The AtDsPTP1 protein is an active phosphatase which can inactivate AtMPK4 protein in vitro (Gupta et al., 1998). However, little is known about its biological functions under osmotic stress. In this study, the dsptp1 mutant shows enhanced tolerance to osmotic stress during seed germination and seedling establishment. This DsPTP positively regulates ABA accumulation and its signalling pathway in response to osmotic stress.

Materials and methods

Plant materials and growth conditions

The T-DNA insertion mutant dsptp1 (SALK_092811) was obtained from the Arabidopsis Biological Resource Centre (http://www.arabidopsis.org/). It was grown and screened for homozygosity. All seeds were of the Columbia ecotype: mutant, WT, overexpression (OE), and complemented (Com). Arabidopsis thaliana L. plants were kept in a growth chamber with a 16 h photoperiod at a photon flux density of ~200 µmol m⁻² s⁻¹ at day/night temperature of 23/20°C, and a relative humidity of 90%.

Stress and ABA treatments

Two-week-old Arabidopsis seedlings on MS plates were transferred to filter papers saturated with different concentrations of mannitol or ABA solution and incubated for different times.

Seed germination assays

WT, dsptp1-mutant, OE, and Com line seeds (>100 seeds for each replicate) were surface sterilized. The seeds were sown on MS medium (Murashige and Skoog, 1962; 1 × MS salts, 10 g l⁻¹ sucrose, and 10 g l⁻¹ agar, pH 5.7) with or without either different osmotic stress-generator solutions or ABA solutions and then incubated at 23°C with a 16 h light photoperiod. The number of planted and germinated seeds was recorded 7 d after being sown on the medium. Radicle emergence of >1 mm indicated seed germination. Three replicate plates were used for each treatment.

Root elongation measurements

Arabidopsis seeds were sown on MS medium as above, stratified for 3 d, and then incubated at 23°C for 7 d. For root elongation measurements, 15 seeds were used per replicate, and three replicates were made for each treatment. Seven-d-old seedlings with roots 1–1.5 cm long were transferred from agar plates containing MS medium onto a second agar medium supplemented with different concentrations of osmotic stress-generator. Increases in root length were measured after 7 d of treatment (Rosado et al., 2006).

Histochemical analysis of GUS activity

A DNA fragment containing 1139 bp of the upstream region of the ATDsPTP1 gene was amplified by PCR using oligonucleotides incorporating XbaI or BamHI sites at the 5' end [5'-TGCTTGAACCTTGGTTTCTGTCTTGCTC-3'] (XbaI site underlined) and 5'- AAAGATCCGAGGATACGAATTCGCAG-3' (BamHI site underlined). The PCR products were digested with XbaI and BamHI and then cloned into the XbaI-BamHI site of a promoterless GUS expression vector, pBI101.3 (Clontech). The resulting construct, ATDsPTP1pro-GUS, was transferred from Escherichia coli DH5α to Agrobacterium tumefaciens GV3101. Arabidopsis was transformed by vacuum infiltration with Agrobacterium containing ATDsPTP1pro-GUS.
Following the methods described by Bechtold et al. (1993), histochemical localization of independent transgenic lines was performed in 5-bromo-4-chloro-3-indolyl glucuronide (X-gluc) buffer (50 mM sodium phosphate buffer, pH 7.0, 10 mM EDTA, 0.1% Triton X-100, 2% DMSO, 0.5 mM potassium ferrocyanide, 2 mM ml⁻¹ X-gluc) at 37°C for 6–12 h. The stained plants were washed for 30 min with 50–100% ethanol to remove the chlorophyll.

Isolation of total RNA and quantitative real-time RT-PCR

Two-week-old plants were transferred from MS agar plates to Petri dishes and placed on a filter paper soaked with 330 mM mannitol solution osmotic treatment. Total RNA was isolated from Arabidopsis seeds or leaves using an RNeasy Plant mini kit (Qiagen, Valencia, CA, USA) according to the manufacturer’s instructions. A 2 μg aliquot of RNA was reverse transcribed to cDNA with a SuperScript III RT S first-strand cDNA synthesis kit (Invitrogen, Carlsbad, CA, USA). Transcript levels of each gene were measured by quantitative real-time RT-PCR (qRT-PCR) using an iCycler (Bio-Rad, Hercules, CA, USA) with IQ SYBR Green Supermix (Bio-Rad). To standardize the results, the amplification of ACTIN was also determined and used as the internal standard. The data were analyzed with the amplification of an Arabidopsis actin gene. For each sample, the mean value from three qRT-PCRs was used to calculate transcript abundance. The mean values were then plotted with their standard errors. The primers that were used in qRT-PCR are summarized in Supplementary Table S1.

Antioxidant enzyme assays

Frozen leaf segments (0.3 g) were homogenized on ice with 1 ml of 50 mM potassium phosphate buffer (pH 7.0), containing 1 mM EDTA and 1% polyvinylpyrrolidone (PVP). The buffer was mixed with 1 mM ascorbate for the ascorbate peroxidase (APX) assay. The homogenate was centrifuged at 15 000 × g for 20 min at 4°C and the supernatant was immediately used for the following antioxidant enzyme assays. Protein content was determined according to the method of Bradford (1976) with bovine serum albumin (BSA) as the standard.

The total activities of antioxidant enzymes were determined as described previously (Jiang and Zhang, 2001). Total superoxide dismutase (SOD) (EC 1.15.1.1) activity was assayed by monitoring the inhibition of photochemical reduction of nitroblue tetrazolium (NBT). The 2.5 ml reaction mixture contained 50 mM phosphate buffer (pH 7.8), 13 mM methionine, 75 mM NBT, 2 mM riboflavin, 0.1 mM EDTA, and 20 μl of enzyme extract. The reaction mixtures were illuminated for 15 min at a light intensity of 5000 µmol m⁻² s⁻¹. The inhibition of photochemical reduction of nitroblue tetrazolium was measured by monitoring the absorbance at 550 nm without NADPH (Jiang and Zhang, 2001).

Lipid peroxidation was evaluated according to the method of Heath and Packery (1968) with slight modification; the reaction solution was heated in boiling water for 15 min. The MDA content was measured from 0.5 g of two-week-old Arabidopsis seedlings. The results are expressed as μmol g FW⁻¹ of seedlings and correspond to means of measurements carried out with four extracts.

Proline assays

Four-week-old dsptp1 and WT (Col0) seedlings grown on soil were soaked with 330 mM mannitol or 400 mM sorbitol solution for different times. After treatment, the samples were frozen in liquid nitrogen and kept at −80°C for the proline assay. Proline concentration was determined following the methods described by Bates (1973).

Malondialdehyde (MDA) measurements

To measure ion leakage in mannitol-treated seedlings, two-week-old WT and dsptp1 seedlings grown on MS agar plates were carefully removed from the plate, rinsed briefly with distilled water, and placed in solutions containing 550 mM mannitol for different times. After treatment, seedlings were rinsed briefly with distilled water and placed immediately in a tube with 5 ml of water. The tube was agitated gently for 3 h before the electrolyte content was measured. Three repetitions of each treatment were conducted.

Determination of endogenous ABA content

For the measurement of endogenous ABA, Arabidopsis leaves were ground in liquid nitrogen with the addition of 1 ml of distilled water per 0.2 g of frozen ground tissue, and then shaken at 4°C overnight. The homogenates were centrifuged at 12 000 × g for 20 min at 4°C, and the supernatant was used directly for ABA assay. ABA analysis was carried out using RIA (radioimmune assay), as described by Quarrie et al. (1988). The reaction mixture (450 μl) contained 200 μl of phosphate buffer (pH 6.0), 100 μl of diluted antibody (Mac 252) (Abcam) solution (the antibody Mac252 was dissolved in PBS containing 5 mg ml⁻¹ BSA and 4 mg ml⁻¹ PVP, 100 μl of [3H]ABA (~8000 cpm) solution, and 50 μl of crude extract. The mixture was incubated at 4°C for 45 min and bound radioactivity was measured in 50% saturated (NH₄)₂SO₄-precipitated pellets with a liquid scintillation counter (Ye et al., 2011).

Generation of the DsPTP1-overexpressing (DsPTP1-OE) line and DsPTP1-complemented (DsPTP1-Com) line

Full-length Arabidopsis DsPTP1 cDNA was obtained by using reverse transcription-PCR, cloned into the pENTR-TOPO cloning vector (Invitrogen) and sequenced. After the LR reaction, DsPTP1 cDNA was inserted into the pGWBS vector (a gift from Prof. Liang, YangZhou University) which had a 35S promoter; this vector was transformed into Col0 wild-type and DsPTP1-complemented (DsPTP1-Com) line

Accession numbers

Sequence data from this article can be found in the Arabidopsis Genome Initiative or GenBank/EMBL databases under the following accession numbers: DsPTP1, At3g23360; DREB2A, At5g05410; RDR2, At5g25610; ICK1, At2g23430; ABF1, At1g49720; COR15A, At2g42540; ERD1, At1g51070; ZEP, At5G67030;
Results

Phenotypic analyses of the dsptp1 mutant

To identify additional osmotic signalling components during seed germination, we obtained Arabidopsis T-DNA insertion mutants for the genes encoding various protein phosphatases. We also performed screening to identify any mutation that could lead to alteration in resistance to osmotic stress during seed germination. As shown in Fig. 1, dsptp1 shows enhanced tolerance to osmotic stress. The dsptp1 mutant carries a T-DNA insertion in the At3g23610 of the AtDsPTP1 gene. The results of real-time PCR and RT-PCR show that dsptp1 is a loss-of-function mutant because the AtDsPTP1 transcript level was hardly detected in the mutant, but it was obviously enhanced in the DsPTP1-OE line (OE-1, 2, 3, 4, 5, 6, 7) compared to the wild type, and it returned to a level similar to the wild type in the DsPTP1-Com line (Figs 1A, B; Fig. 2B). For this study we selected three independent transgenic lines (OE-5, 6, 7) that show high expression levels of DsPTP1 compared with the wild type. Under normal growth conditions in MS medium, no difference in germination percentage was observed among the WT, dsptp1 mutant, OE line (OE-5, 6, 7) and Com line seeds. However, the dsptp1-mutant seeds exhibited a significantly higher seed germination percentage than WT, while the OE line exhibited a lower seed germination percentage than WT (Figs. 1C, D; Supplementary Figure S1A, B). The Com line rescued the seed germination percentage to a level similar to that for WT seeds when compared with OE line seeds in MS medium supplemented with mannitol.

To determine the sensitivity of the dsptp1 mutant to osmotic stress during seed germination, different concentrations of mannitol (330 mM, 385 mM, and 440 mM) and sorbitol (300 mM, 350 mM, and 400 mM) were supplied in the medium. The results show that the dsptp1 mutant exhibited an obviously higher seed germination percentage than WT, whereas the OE line exhibited the lowest seed germination percentage with the increasing mannitol and sorbitol concentrations (Fig. 1D; Supplementary Figures S1B, C).

Overexpression of DsPTP1 decreases osmotic tolerance in Arabidopsis

We generated the DsPTP1-OE lines and the DsPTP1-Com lines. The OE lines showed an increase in At3g23610 at the AtDsPTP1 transcript level relative to the WT plants, and the Com line showed a similar transcript level of AtDsPTP1 compared with the WT plants (Figs 1B, 2B). The seedlings of the OE lines, Com lines, dsptp1 mutant, and WT (Col0) were grown under osmotic stress. Their primary root growth was measured. Root growth of dsptp1-mutant plants was hyposensitive to mannitol (Fig. 2A, C; Supplementary Figure S1A, B) and sucrose (Fig. 2D; Supplementary Figure S1C) compared with that of WT plants (Col0). There was a similar result with a low concentration of sucrose in MS, which removes the sucrose (Supplementary Figure S4). By contrast, the OE lines were relatively more sensitive to osmotic agents than the WT (Fig. 2A, C, D; Supplementary Figure S1A, B, C), and the Com line rescued the root elongation of dsptp1 to a level similar to WT (Figs 2A, C, D). These data indicate that AtDsPTP1 decreases osmotic stress tolerance in Arabidopsis.

Expression patterns of AtDsPTP1

We constructed a chimeric gene consisting of the ATDsPTP1 promoter fused to a GUS reporter gene (ATDsPTP1pro-GUS) to analyse the expression patterns of GUS activity driven by the ATDsPTP1 promoter in transgenic Arabidopsis plants. Spatiotemporal expression analysis showed GUS expression in seed endosperm (Fig. 3B), pollen grains (Fig. 3C, G), and abscission zones of siliques (Fig. 3I), but not in mature embryo (Fig. 3A), rosette, and cauline leaf (Fig. 3E, F). Strong GUS activity was detected in leaf petioles and roots of rosette plants when the transgenic plants were exposed to high osmolarity solutions (Fig. 3I, J). Similarly, strong GUS staining was observed in the seed coat (Fig. 4E, G, H), but not in the embryo (Figs. 4A, C, D) of dry and 3-d-germinating seeds that were exposed to both hyperosmotic solutions. These results suggest that the expression of the AtDsPTP1 gene is upregulated in response to external osmotic changes.

We also assayed the transcript level of DsPTP1 in germinating Arabidopsis seeds from 3 to 12 h after imbibing and in 1 and 2 d seedlings under different treatments using qRT-PCR. In accordance with the results of GUS staining, the AtDsPTP1 expression in WT seeds was sharply induced by mannitol (Fig. 4I) and sorbitol (Fig. 4J) solutions. The transcript level of AtDsPTP1 in WT seedlings was also enhanced at 48 h after mannitol (Fig. 4K) and sorbitol (Fig. 4L) treatments. These results indicate that AtDsPTP1 is induced by osmotic stress.

Increased proline content and resistance to oxidative damage in dsptp1 plants

Proline accumulation has adaptive functions in plant stress tolerance, acting as a compatible osmolyte that stores carbon and nitrogen (Hare et al., 1997). Previous studies in vitro showed that proline can be a reactive oxygen species (ROS) scavenger (Smirnoff and Cumbers, 1989), and a molecular chaperone that stabilizes protein structure. Proline accumulation can buffer cytosolic pH and balance cell redox status; it is also part of the stress signal that influences adaptive responses (Maggio et al., 2002). Proline accumulation in the dsptp1 mutant and WT plants treated with mannitol and sorbitol was measured. As shown in Fig. 5, the proline content in both dsptp1 mutant and WT plants increased in response to 330 mM mannitol treatment. However, the increase in the dsptp1-mutant plants was more remarkable than that in the WT plants at 48 h after mannitol treatment (Fig. 5A). A similar trend in proline content was observed between the dsptp1 mutant and WT plants treated with 400 mM sorbitol for 36 h (Fig. 5B).
AtDsPTP1 regulates osmotic signalling in *Arabidopsis*

MDA is produced by lipid peroxidation because of the effect of ROS (Halliwell and Chirico, 1993). As the best-characterized product of lipid peroxidation, MDA is often used as a biomarker to measure cell membrane injury and cell and tissue oxidative damage (Esterbauer *et al.*, 1991). To determine the degree of cellular injury, we determined the MDA content in the *dsptp1* mutant and WT plants with 550 mM mannitol treatment. The MDA content increased in both

**Fig. 1.** The *dsptp1* mutant shows an increased germination percentage under osmotic stress. (A) Structure of the *AtDsPTP1* gene. The insertion of T-DNA in the *dsptp1* mutant is shown as a triangle. Exons are shown as black boxes and introns as thin lines. (B) Real-time RT-PCR analysis for *AtDsPTP1* transcript. The *AtDsPTP1* transcript was present in total RNA from the WT, Com, and OE-5 lines but absent in the *dsptp1*-mutant plants. Relative expression levels of *AtDsPTP1* are normalized to *AtACTIN2* transcript levels. Values presented are mean ± SE of three different experiments. (C) Germination of WT (Col0), *dsptp1*-mutant, Com, and OE-5 line *Arabidopsis* seeds in normal and mannitol-containing media. (D) Percentage seed germination of *dsptp1*-mutant plants with and without different osmotic treatments. *Arabidopsis* seeds of WT (Col0) and *DsPTP1* mutants were sown in MS medium with or without osmotic treatments including 330, 385, and 440 mM mannitol (left) and 300, 350, and 400 mM sorbitol. Values presented are mean ± SE of three different experiments.
dsptp1-mutant and WT plants after the treatment. However, the increase in the dsptp1-mutant seedlings was less than half of that in the WT seedlings after the treatment. Although the dsptp1-mutant seedlings had slightly lower MDA content than the WT seedlings even without stress treatment, the increase in the MDA level was significantly lower in the mutant than in the WT plants after 12 and 24 h of mannitol treatment (Fig. 5C). Similar results were obtained with the 330 mM mannitol treatment (Supplementary Figure S5).

After the dsptp1-mutant and WT seedlings were treated with 550 mM mannitol, ion leakage was measured as an indicator of osmotic stress-induced cellular damage. Although the dsptp1-mutant seedlings had no obvious differences in ion leakage compared with the WT plants without stress treatment, mannitol treatment resulted in a sharper increase in electrolyte leakage in the WT plants than in the dsptp1-mutant plants (Fig. 5D). These data indicate that the dsptp1-mutant plants are less sensitive to osmotic stress.
To investigate the effects of AtDsPTP1 on the activities of antioxidant enzymes, we determined the total activities of antioxidant enzymes, including APX, SOD, GR, and CAT. Fig. 6 shows that the osmotic stress-induced APX (Fig. 6A), SOD (Fig. 6B), GR (Fig. 6C), and CAT (Fig. 6D) activities of the dsptp1-mutant plants are significantly higher than those
of the WT plants. These findings suggest that \textit{dsptp1} has an enhanced ability to scavenge the extra ROS under osmotic stress to maintain the equilibrium between ROS production and scavenging. These data indicate that the \textit{dsptp1}-mutant plants can attenuate cell damage caused by osmotic stress.

\textbf{The dsptp1 mutant enhances expression of osmotic responsive genes}

To determine the function of \textit{AtDsPTP1} in signalling pathways in response to osmotic stress, we analysed the expression of genes regulated by abiotic stress in WT and \textit{dsptp1}-mutant plants with or without mannitol treatment. As shown in the real-time PCR results in Fig. 7, significant differences in the expression of general stress-responsive genes (e.g. \textit{RD22} and \textit{ICKI}) and ABA-response genes (e.g. \textit{ABF1}) were found between the WT and the \textit{dsptp1}-mutant plants. In addition, osmotic stress-induced expression was different in the \textit{dsptp1}-mutant and WT seedlings for \textit{ERD1} (early response to dehydration 1) (Fig. 7F), \textit{COR15A} (Fig. 7E), and \textit{DREB2A} (Fig. 7A). \textit{ERD1} encodes a chloroplast-targeted chaperonin possibly involved in proteolysis (Weaver \textit{et al.}, 1998), \textit{COR15A} encodes a chloroplast-targeted LEA protein (Artus \textit{et al.}, 1996), and \textit{DREB2A} encodes a transcription factor activated in the early stages of the \textit{ERD1} osmotic stress response (Kiyosue \textit{et al.}, 1994).

Shortly after osmotic treatment, \textit{DREB2A} and \textit{RD22} transcripts accumulated to significantly higher levels in the WT than in the \textit{dsptp1}-mutant plants (Figs 7A, B). By contrast, the induction of \textit{ICKI}, \textit{ABF1}, \textit{COR15A}, and \textit{ERD1} expression was higher in the \textit{dsptp1}-mutant plants than that in the WT plants after osmotic treatment (Figs 7C–F). The compromised induction of different dehydration-responsive genes together with reduced sensitivity to osmotic stress in \textit{dsptp1}
AtDsPTP1 regulates osmotic signalling in Arabidopsis  

indicated that DsPTP1 is possibly important in the dehydration-signalling pathway.

The dsptp1 mutant reduces ABA content and suppresses the ABA-signalling pathway under osmotic stress

To test the sensitivity of the dsptp1 mutant to ABA, we determined the effect of ABA on the germination, cotyledon expansion, and root elongation of dsptp1. The radicle emergence of seeds was observed after 7 d of sowing on MS medium supplemented with different ABA concentrations (Fig. 8A; Supplementary Figure S2A). The inhibition of seed germination by ABA in the dsptp1-mutant plants was less obvious than that in the WT plants, whereas the OE-line seeds were more sensitive to ABA than were the WT seeds. Seed germination percentage in the Com lines was similar to that of WT seeds (Fig. 8A).

The ABA contents in the dsptp1-mutant and WT plants were also measured using a radioimmunoassay (RIA) method. In the absence of stress treatment, WT and dsptp1 leaves had similar ABA contents (Fig. 8C). When the plants were treated with 440 mM mannitol for the indicated time, the endogenous ABA level in the WT plants was higher than that in the dsptp1-mutant plants.

To investigate the function of DsPTP1 in ABA accumulation in response to osmotic stress, we analysed the expression of genes encoding enzymes for ABA biosynthesis and catabolism in the WT and dsptp1-mutant plants (Nambara and Marion-Poll, 2005). The qRT-PCR results showed that the expressions of all the ABA-biosynthesis genes and the catabolic genes are similar without osmotic stress. The expression level of all the genes assayed for ABA biosynthesis (ZEP, NCED3, and AAO3) and catabolism (CYP707A3...
and CYP707A4) increased after osmotic stress treatment. However, the magnitudes of the increases varied. The expression level of the biosynthesis gene NCED3 markedly increased to a higher level in the WT plants compared with the dsptp1-mutant plants (Fig. 7D). By contrast, the catabolic gene CYP707A4 was expressed at an obviously lower level in the WT plants compared with the dsptp1 mutant (Fig. 7D). This result indicates that DsPTP1 affects the endogenous ABA content by regulating the genes for ABA biosynthesis and catabolism after osmotic stress treatment.

To explore the function of AtDsPTP1 in ABA-signalling pathways in response to osmotic stress, we analysed the expression of genes that regulate ABA responses in WT and dsptp1-mutant plants both before and after mannitol treatment. The results of real-time PCR showed significant differences between the WT and the dsptp1-mutant plants in terms of the expression of ABA-regulated genes, such as ABI1, ABI3, and ABI5 (Fig. 9). This indicates that AtDsPTP1 probably acts upstream of these genes in the ABA pathways. The induction of ABI3 (Fig. 9B) and ABI5 (Fig. 9D) expression was significantly lower in dsptp1-mutant plants than in the WT plants with mannitol treatment. By contrast, the induction of ABI1 increased in the dsptp1-mutant plants compared with the WT plants after osmotic stress (Fig. 9A). We also measured the expression of ABA-response genes (ABI1, 3, 4, 5) in the WT and dsptp1 mutant under 20 µM ABA treatment; the dsptp1 mutant showed less sensitivity to ABA compared with the WT (Supplementary Figure S3).

Discussion

Protein kinases and PPs have critical functions in plant development and stress responses (Fujii and Zhu, 2012). Members from different sub-families of PPs were studied for their biological functions (Schweighofer et al., 2004; Schweighofer and Meskiene, 2008; Bartels et al., 2010). As a member of the unique group that is capable of dephosphorylating both serine/threonine and tyrosine, DsPTP1 is little known, especially in plant stress responses. Thus, we characterized a dsptp1 mutant that is hyposensitive to osmotic stress during seed germination and root elongation of seedlings (Figs 1, 2; Supplementary Figure S1). With the genetic evidence,
we studied the biological function of the \textit{DsPTP1} gene in response to stress conditions. The expression of the \textit{DsPTP1} gene is induced by osmotic stresses both in seedlings (Fig. 3K, L) and seeds (Fig. 4I, J). Knockout of the \textit{AtDsPTP1} gene results in enhanced tolerance, whereas overexpression of the \textit{AtDsPTP1} gene results in an attenuated tolerance compared
with the wild type, and the AtDsPTP1-complemented lines rescued the tolerance of the dsptp1 mutant to the wild-type level under these stress conditions (Figs 1, 2; Supplementary Figure S1). Our results indicate that the AtDsPTP1 gene is involved in osmotic stress responses and possibly has a negative regulatory function.

A promoter-reported fusion analysis indicated that DsPTP1 is strongly expressed in the endosperm layer in the seed coat of dry seeds (Figs 3B, 4E), but that this disappears after imbibition (Fig. 4F). Seed coats have a key function in maintaining seed dormancy (Holdsworth et al., 2008), suggesting that DsPTP1 is involved in regulating seed germination; the induced expression of DsPTP1 occurs at the base and roots of rosettes, both of which are important for the maintenance of root elongation under stress conditions (Beemster and Baskin, 1998). These results further prove that AtDsPTP1 is a negative regulator in plant growth and development under stress conditions, such as seed germination and root elongation.

Although most protein phosphatases have many functions in controlling plant growth and development, the pathways they are involved in can vary. We studied the physiological and biochemical responses of the dsptp1 mutant to osmotic stress. As shown in Fig. 5, all physiological indexes, such as ion leakage, suggest a better performance of the dsptp1 mutant under osmotic stress than WT. Proline accumulates largely in cells as an osmolyte to help in osmotic adjustment under stress. The dsptp1-mutant plants had higher proline accumulation than the WT plants under osmotic stress. Proline accumulation modulates pH changes and reduces cell damage by osmotic stress (Zhu, 2002). The levels of MDA, a biomarker of cell membrane injury, and ion leakage, an indicator of osmotic-induced cellular damage, increase less under osmotic stress in the dsptp1 mutant than in WT.

ROS are important signalling molecules that accumulate under many stress conditions. However, high ROS concentrations can be highly toxic to plants (Apel and Hirt, 2004; Ye et al., 2011). Thus, we measured the antioxidant enzyme activities in the dsptp1-mutant and WT plants (Fig. 6). Increased proline content reduces the inhibitory effects of osmotic stress on enzyme activity, increases the thermal stability of enzymes, and prevents the dissociation of enzyme...
complexes (Hayashi et al., 1997). Therefore, we suspect that proline accumulation causes the enhanced activity of all four antioxidant enzymes in the dsptp1 mutant relative to the WT plants, which could explain why the MDA content in the mutant plant is lower than that in the WT plants.

The results demonstrate that DsPTP1 is induced by osmotic stress in the WT plants, thereby suppressing the accumulation of many metabolites that ameliorate the effects of osmotic stress and changing the expression pattern of a subset of dehydration-responsive genes (Fig. 7). Knockout of the AtDsPTP1 gene in the dsptp1 mutant plants results in better adaption to osmotic stress than in the WT plants. The compromised induction of different dehydration-responsive genes together with reduced sensitivity to osmotic stress in dsptp1 indicates that DsPTP1 is possibly important in the dehydration signalling pathway (Fig. 7).

As a stress phytohormone, ABA has a pivotal regulatory function in numerous stress responses, including osmotic stress (Boudsocq and Lauriere, 2005; Rosado et al., 2006; Cutler et al., 2010). To study how the DsPTP1 gene controls the responses of plant to osmotic stress, we examined the relationship between the DsPTP1 gene and ABA using the dsptp1-mutant plants. The inhibitory effects of ABA on seed germination and root elongation were suppressed by the mutation of the AtDsPTP1 gene but enhanced by the overexpression of the AtDsPTP1 gene (Fig. 8A, B; Supplementary Figs S2A, B). Meanwhile, the seed germination percentage (Fig. 8A) and root elongation (Fig. 8B) were rescued to a level similar to the wild type by complementing the corresponding gene in the dsptp1 mutant. Similar effects were noted under osmotic stress treatment (Figs 1, 2). These results strongly suggest that the AtDsPTP1 gene is involved in the Arabidopsis...
ABA-signalling pathway, mediating the inhibitory effect of ABA in plants under osmotic stress.

To study the relationship between AtDsPTP1 and the ABA pathway, we determined the ABA contents in the dsptp1 mutant and WT plants. Knockout of the DsPTP1 gene decreased the ABA content in the dsptp1-mutant plants compared with the WT plants. This finding may be attributed to the downregulated expression of the rate-limiting, ABA-biosynthesis enzyme NCED3, and the significantly upregulated expression of the ABA-catabolic enzyme CYP707A4 (Fig. 8).

Thus, downregulation of AtDsPTP1 can decrease ABA content by suppressing ABA biosynthesis and increasing ABA catabolism. The expression of genes in the ABA-response pathway show similar results (Fig. 9); downregulation of DsPTP1 decreases the gene expression of the positive regulators in ABA signalling, such as ABI3 and ABI5, and increases the expression of the negative regulator, ABI1, under osmotic stress conditions. This phenomenon can also explain why the mutant plant is less sensitive to osmotic stress as well as the ABA treatment. These findings suggest that the dsptp1-mutant plants are more tolerant to osmotic stress than the WT plants.

All of these results show that tolerance of dsptp1 to osmotic stress is mainly connected to proline accumulation. With a higher concentration of proline accumulation in dsptp1, there is less injury under osmotic stress. Thus, the dsptp1 mutant accumulated less ABA, which led to a decreased ABA response compared with the WT under osmotic treatment (Fig. 8C, D, Fig. 9; Supplementary Figure S5), just as previously reported (Lv et al., 2011). The dsptp1 mutant also showed less sensitivity to exogenous ABA, and this is also connected with the lower accumulation of, and decreased the sensitivity to, ABA (Fig. 8A, B; Supplementary Figure S2). These results show that DsPTP1 acts as a negative regulator in osmotic stress signalling during Arabidopsis seed germination and seedling establishment.

We characterized a dsptp1 mutant of Arabidopsis. The DsPTP1 gene is induced significantly by osmotic stress and has a negative regulatory function during seed germination and seedling establishment. Its mutation results in better performance in the dsptp1-mutant than WT plants under osmotic stress. The dsptp1-mutant plants accumulated more proline than WT plants under osmotic stress; proline functions in osmotic adjustment in cells. The dsptp1-mutant plants exhibit attenuated sensitivity to osmotic stress damage than the WT plants, resulting in reduced MDA content, reduced ion leakage, and enhanced antioxidant enzyme activities (APX, SOD, GR, and CAT). The accumulation of ABA in response to osmotic stress is also controlled by downregulation of DsPTP1 gene expression, which reduces expression of ABA-biosynthesis genes and increases expression of ABA-catabolism genes. The DsPTP1 gene is also involved in the ABA-signalling pathway, regulating the expression of ABI genes such as ABI1, ABI3, and ABI5. In addition, DsPTP1 regulates the expression of a series of dehydration-responsive genes under osmotic stress. The aforementioned results show that DsPTP1 acts as a negative regulator in osmotic stress signalling during Arabidopsis seed germination and seedling establishment.

**Supplementary material**

Supplementary data can be found at JXB online.

**Supplementary Table S1.** Primers used for real-time RT-PCR assays.

**Supplementary Figure S1.** Comparison of WT, dsptp1-mutant, OE-6, and OE-7 lines in seed germination under osmotic stresses.

**Supplementary Figure S2.** Comparison of WT, dsptp1-mutant, OE-6, and OE-7 lines in seed germination and root elongation under ABA treatment.

**Supplementary Figure S3.** The dsptp1 mutant shows altered expressions of ABA-regulated genes under ABA treatment.

**Supplementary Figure S4.** Comparison of root elongation in the OE, WT, and dsptp1-mutant lines on medium with or without sucrose.

**Supplementary Figure S5.** Comparison of MDA content between the WT and dsptp1 mutant under treatment with 330 mM mannitol.

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**References**


AtDsPTP1 regulates osmotic signalling in Arabidopsis


