Major latex protein-like protein 43 (MLP43) functions as a positive regulator during abscisic acid responses and confers drought tolerance in Arabidopsis thaliana

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Abstract

Drought stress is one of the disadvantageous environmental conditions for plant growth and reproduction. Given the importance of abscisic acid (ABA) to plant growth and abiotic stress responses, identification of novel components involved in ABA signalling transduction is critical. In this study, we screened numerous Arabidopsis thaliana mutants by seed germination assay and identified a mutant mlp43 (major latex protein-like 43) with decreased ABA sensitivity in seed germination. The mlp43 mutant was sensitive to drought stress while the MLP43-overexpressed transgenic plants were drought tolerant. The tissue-specific expression pattern analysis showed that MLP43 was predominantly expressed in cotyledons, primary roots and apical meristems, and a subcellular localization study indicated that MLP43 was localized in the nucleus and cytoplasm. Physiological and biochemical analyses indicated that MLP43 functioned as a positive regulator in ABA- and drought-stress responses in Arabidopsis through regulating water loss efficiency, electrolyte leakage, ROS levels, and as well as ABA-responsive gene expression. Moreover, metabolite profiling analysis indicated that MLP43 could modulate the production of primary metabolites under drought stress conditions. Reconstitution of ABA signalling components in Arabidopsis protoplasts indicated that MLP43 was involved in ABA signalling transduction and acted upstream of SnRK2s by directly interacting with SnRK2.6 and ABF1 in a yeast two-hybrid assay. Moreover, ABA and drought stress down-regulated MLP43 expression as a negative feedback loop regulation to the performance of MLP43 in ABA and drought stress responses. Therefore, this study provided new insights for interpretation of physiological and molecular mechanisms of Arabidopsis MLP43 mediating ABA signalling transduction and drought stress responses.

Key words: ABA signal reconstitution, abscisic acid, drought stress, metabolite profile, MLP43, reactive oxygen species, SnRK2.6.
Introduction

Abiotic stresses greatly affect plant growth and crop production. To date, plants have evolved many mechanisms to adapt and survive against these stresses, which include developmental, morphological, physiological and biochemical strategies. Plant hormones play essential roles in promoting and mediating these defense responses (Peleg and Blumwald, 2011). Abscisic acid (ABA) is regarded as a key signal involved in regulating the response of plants to various stresses, and particularly in regulating drought stress responses when plants experience water deficit (Cutler et al., 2010; Lee and Luan, 2012). ABA production increases radically under drought stress conditions and stimulates stomatal closure, changing the expression of various osmotic stress-responsive genes (Kim et al., 2010). In recent years, significant research progress has been made in studies using plants bearing gene mutations involved in hormone-biosynthetic and signalling transduction pathways, and to the identification of the ABA receptors PYR/PYL through chemical genetic approaches (Park et al., 2009; Ma et al., 2009; Hubbard et al., 2010). Given the importance of ABA to plant physiology and development, identification of novel components involved in ABA signalling transduction is critical.

Major latex protein (MLP) was first identified from the latex of the opium poppy (Papaver somniferum) (Nessler et al., 1990; Nessler and Burnett, 1992). The orthologues of MLP in Papaver somniferum of the opium poppy (Nessler et al., 2005) were later found in Arabidopsis, soybean and tobacco (Aggelis et al., 2008). It is known that MLPs are down-regulated by oxidative stress through modulation of the ABA receptors PYR/PYL and ABF1 in yeast. An interesting study by Chen and Dai (2010) indicated that MLPs are down-regulated in Arabidopsis by ABA and drought-stress responses in Arabidopsis through modulating primary metabolism profiling and gene expression. Reconstitution analysis ofMLP cDNA in plants bearing gene mutations involved in ABA signalling transduction and could directly interact with SnRK2.6 and ABF1 in yeast.

Materials and methods

Arabidopsis thaliana ecotype Columbia (Col-0) was used in this study and all transgenic plants were generated in a Col-0 background. The line of MLP43 mutant (Salk_109337 and Salk_033347) was obtained from the Arabidopsis Biological Resource Center (ABRC; http://arabidopsis.org/abrc/) and identified by PCR. Primers used are listed in Supplementary Table S1 at JXB online. The mutants of osti-1 (Mustilli et al., 2002), abal-1 (Koornneef et al., 1982) and abal-1 (Koornneef et al., 1984) are derived from the Arabidopsis accession Landsberg erecta (Ler). The pry1/pry1/pry1 triple mutant (Park et al., 2009) is derived from the Arabidopsis accession Co-0. Seeds were surface sterilized and sown on Murashige and Skoog (MS) agar plates containing full-strength MS salts, 0.8% (w/v) agar, and 1% (w/v) sucrose. Germination assay was performed with or without ABA on MS plates (Sigma, A1049). The seeds were stratified at 4°C for 4 d in darkness and then transferred to growth chamber with 16 h/8 h light/dark cycle at 23°C, or were directly sown in soil after stratification under the same conditions.

Plasmids construction and transgenic plant generation

MLP43 cDNA was amplified using the primers MLP43-F and MLP43-R and cloned into Pro35S::GFP to generate Pro35S::MLP43-GFP fusion construct. The fused protein was then digested by XhoI/SacI and inserted into a binary vector pBA to generate pBA-MLP43-GFP construct. Promoter fragment of MLP43 (-1769 bp before start codon ATG) was amplified using primers ProMLP43-F and ProMLP43-R and subsequently cloned into Pro35S::GFP to generate pBA-MLP43-GFP construct. The primers used for plasmids construction are listed in Supplementary Table S2. The primers used for plasmids construction are listed in Supplementary Table S2. The primers used for plasmids construction are listed in Supplementary Table S3. The mutated ABG-3 was generated by introducing Agrobacterium tumefaciens (strain GV3101) carrying the corresponding plasmids through floral dip-mediated infiltration into Col-0 background (Clough and Bent, 1998). Complementation transgenic plants of Com-3 were generated by introducing a pBA-MLP43-GFP construct into MLP43 mutant background.

GUS histochemical analysis and subcellular localization

GUS signals were detected according to the method described by Jefferson et al. (1987). Plants were pretreated with or without 100 μM ABA for 3 h, and then immersed in 90% acetone for 30 min. After incubation in the GUS staining solution (0.5 mg/ml X-Gluc, 50 mM
PBS, pH 7.0; 5.0 mM potassium ferricyanide, 5.0 mM potassium ferrocyanide, 0.1% Triton X-100) at 37°C over night, the stained plants were washed with 70% ethanol overnight. Images were taken with an inverted microscope (SMZ1500, Nikon). For subcellular localization of MLP43, we transformed the plasmids into Arabidopsis rosette leaves (Col-0) by bombardment. Images were taken with an inverted microscope (TE2000U, Nikon), equipped with cool CCD (CoolSNAP HQ2, Roper Scientific). GFP fluorescence was acquired with 488 nm excitation, and the chloroplast auto-fluorescence was acquired with 543 nm excitation.

Drought treatment, water loss analysis, and stomatal aperture measurement
For measurement of drought tolerance, water was withheld from 14-day-old plants comparable in size and growing in pots. After 21 d of drought treatment, the plants were re-watered. Survival rates were determined and the plants were photographed 2 d after re-watering. For measurement of water loss from detached leaves, the rosette leaves were detached from four-week-old plants and weighed at the indicated times. To analyse stomatal apertures, we incubated rosette leaves in a solution containing 50 mM KCl, 10 mM CaCl2 and 10 mM MES (pH 6.15) for 3 h under light condition. ABA was then added to the solution to a final concentration of 50 μM. Stomatal apertures were then measured after 30 min and 1 h of ABA treatment, respectively. For each experimental repeat, at least 50 stomata were counted and measured by photoshop software. The values of stomatal width to length ratios (V) were defined as: V≥0.5, open; 0.5>V≥0.25, partially open; and V<0.25, closed.

Comparison of EL, ROS contents and antioxidant enzymes activities
EL was determined from the detached aerial parts of drought-stressed plants with the indicated time points. The detailed procedure was performed as described by Wang et al. (2013). Superoxide radicals (O2-) and hydrogen peroxide (H2O2) were detected by nitroblue tetrazolium (NBT) staining and 3,3′-diaminobenzidine (DAB) staining, respectively, as described previously (Ramel et al., 2009). Two-week-old seedlings were grown in soil, and then withheld water for the number of days indicated. Quantification of H2O2 content was determined using the method described by Hu et al. (2012). The activities of antioxidant enzymes were measured after drought treatment application followed by the procedure described by Wang et al. (2013).

Gene expression analysis by real-time quantitative RT-PCR
Two-week-old plants were treated as indicated phytohormones or abiotic stresses. Total RNA was extracted using a plant RNA purification kit (Tiangen, Beijing, China). Equal amounts of RNA were used for reverse transcription with ReverTra Ace-α-TM (TOYOBO, Tokyo, Japan) according to the manufacturer’s instructions. The primers used in qRT-PCR were designed using web tool GenScript (http://jtreeview.sourceforge.net/). The primers used for qRT-PCR experiment are listed in Supplementary Table S4.

Metabolite profiling by gas chromatograph time-of-flight mass spectrometry
Plant samples for metabolite profiling were withheld water for two weeks from the 15th day after sowing in the growth chamber, and then all seedlings were harvested and immediately frozen in liquid nitrogen. The experimental procedure for extract preparation was performed as described previously (Lisec et al., 2006). The total extracts were quantified by performing chromatography on GC-TOF MS (Agilent 7890A/5975C, USA). The detailed procedure has been described by Shi et al. (2014), with the data representing the mean values of three independent experimental repeats. The results were analysed using the Cluster 3.0 program (http://bonsai.hgc.jp/~mdehoon/software/cluster/) and visualized using Java Treeview (http://jtreeview.sourceforge.net/).

Transient expression assay
Mesophyll protoplasts were isolated from four-week-old Col-0 plants according to the methods described previously (Yoo et al., 2007). All of the plasmids used in this assay were prepared through purification with caesium chloride/ethidium bromide (Sambrook et al., 1989). For the luciferase assay, protoplasts were harvested after 12-h incubation under light conditions at 23°C with or without stimuli (50 μM ABA). The activities of LUC and GUS were measured with the GloMax-Multi Jr Single Tube Multimode Reader (Promega, USA). All experiments were repeated at least three times.

Yeast two hybrid (Y2H) assay
The Y2H assay was carried out according to the instructions for the Matchmaker GAL4-based two-hybrid system (Clontech). The full-length sequence of MLP43 was cloned and inserted into pGADT and pGBKKT, respectively. Another two homologous genes, MLP34 and MLP168, were cloned and inserted into pGBKKT. We cloned ABF1, SnRK2.2, SnRK2.3, PYL12/59/9/13 and ABI1 and fused them into the pGADT vector, respectively. The genes of SnRK2.6, SnRK2.8, SnRK2.10, PYR1, ABF1 and ABF3 were cloned and fused into the pGBKKT vector, respectively. The restriction sites and primer sequences for the plasmids used in this assay have been provided in Supplementary Tables S2 and S3, respectively.

Results
The mlp43 mutant was insensitive to ABA during seed germination
To discover other novel regulators and to expand ABA signaling networks during seed germination and abiotic drought stresses, we screened various T-DNA insertion mutants purchased from the ABRC (http://www.arabidopsis.org/) on MS medium containing 1.0 μM ABA during seed germination. The mutant mlp43-1 (Salk_109337) showing insensitivity to ABA was selected for further analysis. T-DNA was inserted into the 5′-UTR of MLP43 (Fig. 1A). Transgenic plants of overexpressed MLP43 (OE-2 and OE-4) was generated by introducing Pro35S::MLP43-GFP plasmids into Col-0 plants. The relative expression level of MLP43 was verified by qRT-PCR (Fig. 1B). The expression levels of MLP43-GFP fusion protein was detected using anti-GFP antibody through western-blot assay (Supplementary Fig. S1A). In the absence of ABA, no obvious differences were observed in germination rates between Col-0 and the mlp43-1 mutant (Fig. 1C, D). However, the mlp43 mutant showed significantly decreased ABA sensitivity on the 1.0 μM ABA by analysing the percentages of emerged radicles and open green cotyledons (Fig. 1E, F). On the 4th day after stratification, about 80% and 25% of Col-0 emerged with radicles and green cotyledons, respectively. However, the corresponding percentages of mlp43-1 were more than 95% and 50%. Overexpressed MLP43 transgenic plants showed much lower germination rates than...
Col-0 plants (Fig. 1E, F). We also examined the ABA sensitivity with another T-DNA insertion Salk line mlp43-2 (Salk_033347) in the seed germination assay. As indicated in Supplementary Fig. S1, this mutant line harbours almost null expression levels of MLP43 and was insensitive to ABA in seed germination. The ABA sensitivity of root growth was also examined after ABA treatment and the results indicated that no significant differences in primary root growth and lateral root number were observed among Col-0, mlp43-1, and MLP43 OE seedlings (Supplementary Fig. S2A, B). Taken together, MLP43 might function as a positive regulator in ABA response during seed germination.

Modulation of MLP43 expression by ABA and abiotic stress treatments

Based on publicly available microarray data (http://bar.utoronto.ca/efp/cgi-bin/efpWeb.cgi; Winter et al., 2007), the MLP43 transcript was inhibited by ABA (30 μM) after 24 h of treatment in seeds, but induced by gibberellic acid 3 (GA3, 5 μM) after 3 and 6 h of treatment, respectively (Fig. 2A, B). The effects of abiotic stresses on MLP43 transcripts were further analysed. Interestingly, cold (4°C), osmotic stress (300 mM d-mannitol), salt (150 mM NaCl) and drought (air dry) negatively regulated MLP43 expression (Fig. 2C). To further confirm the effects of phytohormones and abiotic stresses on MLP43 expression, qRT-PCR was applied to examine relative expression levels of MLP43. The results indicated that MLP43 was actually inhibited by ABA (50 μM, 3 h), drought (water withheld for two weeks) and salt (NaCl, 100 mM for 3 h) treatment, respectively. No significant changes were observed after cytokinin (6-BA), auxin (IAA) or ethylene (ACC) treatment except that GA3 treatment slightly up-regulated MLP43 expression (Fig. 2D). These results showed that ABA and drought treatment decreased MLP43 transcription, which were consistent with the public microarray data.

Overexpressed MLP43 confers enhanced drought tolerance

As the mlp43 mutant showed significantly decreased ABA sensitivity in seed germination, and drought treatment inhibited

Fig. 1. MLP43 was involved in ABA responses in seed germination assay. Asterisk symbols (*) indicate P<0.05 (Student’s t-test). (A) Diagram showing of the T-DNA insertion site of mlp43-1 mutant. (B) Relative expression levels of MLP43 in the mlp43-1 mutant and overexpressed transgenic plants. Expression levels of β-ACTIN8 represent the internal control. Data represent the means ±SEs of three replicated experiments. (C) Seeds growing on MS medium with or without 1.0 μM ABA for 5 d after stratification. Both overexpressed transgenic plants (OE-2 and OE-4) showed a hypersensitive response to ABA. Photographs were taken to document the phenotypes. (D) Germination rates of green cotyledons with the indicated ABA application. Germination rates (%) were scored 5 d after stratification. Data represent means ±SEs of three replicated experiments (n>60 for each experiment). (E) Germination rates of radicle emergence in 1.0 μM ABA plates at the indicated time points. Data represent the means ±SEs of three replicated experiments (n>60 for each experiment). (F) Germination rates of green cotyledons in 1.0 μM ABA plates at the indicated time points. Data represent the means ±SEs of three replicated experiments (n>60 for each experiment). (This figure is available in colour at JXB online.)
MLP43 expression (Figs 1, 2), the responses to drought stress of the mlp43-1 mutant and MLP43-overexpressed plants were further examined. Two-week-old plants grown under normal conditions were withheld water for three weeks, and then rewatered for 2 d. The results indicated that only 20% of mlp43-1 mutants but more than 80% of MLP43 OE plants recovered from wilting after rehydration, while the survival rate of Col-0 was about 58% (Fig. 3A, B). The EL test showed that the mlp43-1 mutant exhibited a significantly higher EL percentage than Col-0, but MLP43 OE plants showed a lower EL percentage relative to Col-0 (Fig. 3C). Transpirational water loss from detached leaves of 4-week-old plants were further compared at room temperature with a humidity of ~50–60%. Much higher water loss rates were detected in the mlp43-1 mutant compared with Col-0, while MLP43 OE plants showed lower water loss rates compared to Col-0 (Fig. 3D).

ABA-induced stomatal closure is usually responsible for plant adaptation to drought stress. We defined the stomatal phases as open, partially open and closed, according to the ratios of width to length of stomatal aperture (Fig. 3E). Under normal conditions, the rates of different stomatal phases were comparable among wildtype (Col-0), mlp43-1 and MLP43 OE. However, after ABA treatment for 1 h, the rates of closed stomata were significantly increased in Col-0, especially in MLP43 OE. In contrast, the mlp43-1 mutant exhibited fewer closed stomata and more partially closed stomata than those in Col-0 and MLP43 OE (Fig. 3E). Together, these results suggested that the improved drought tolerance of MLP43 OE was associated with an increased sensitivity to ABA-induced stomatal closure in MLP43 OE. The complementary overexpressed transgenic plants generated by introducing Pro35S::MLP43-GFP into mlp43-1 were further assessed for drought resistance. The results indicated that the hypersensitivity of mlp43-1 mutant to drought stress could be restored by MLP43 overexpression (Supplementary Fig. S3).

**Tissue-specific expression patterns and subcellular localization of MLP43**

Tissue-specific expression patterns of MLP43 were firstly analysed based on the microarray data available in public resources (Fig. 4A; http://bar.utoronto.ca/efp/cgi-bin/efpWeb.cgi; Winter et al., 2007). The results indicated that MLP43 preferentially expressed in cotyledons and hypocotyls in Arabidopsis, while lower expression levels could be detected in roots, shoots, stems and vegetative rosette leaves (Fig. 4A). Almost no expression patterns could be detected either in dry seed or in imbibed seeds (Fig. 4A). To further confirm the specific expression patterns of MLP43 in Arabidopsis, the promoter sequence of MLP43 (~1769 bps upstream of start code ATG) was cloned and a transgenic plant carrying plasmid ProMLP43::GUS was generated. GUS histochemical signals were analysed in various tissues (Fig. 4B–I). There were predominant GUS signals in cotyledons, primary roots and apical meristems (Fig. 4B–D, H, I). GUS signals also could be detected in rosette leaves, flowers and the abscission zone (Fig. 4E–G) whereas no GUS signals had been examined in hypocotyls, which was inconsistent with the microarray data. We transiently expressed the Pro35S::MLP43-GFP fusion construct into epidermal cells of Arabidopsis rosette leaves by bombardment and observed the subcellular localization...
of the MLP43-GFP fusion protein under a confocal fluorescence microscope. The results indicated that MLP43 were localized in nucleus and cytoplasm in Arabidopsis epidermal cells (Fig. 4J–L).

Mutation of MLP43 increased ROS production and modulated primary metabolites after drought treatment

ABA and drought stress trigger ROS accumulation, and a ROS detoxification mechanism is necessary to enable plant survival under drought stress (Smirnoff, 1993). To characterize whether ROS accumulation was altered in the mlp43-1 mutant, we determined H2O2 and O\(^-\) production by DAB and NBT staining, respectively. The mlp43-1 mutant exhibited a dark colour relative to Col-0 with both DAB and NBT staining after air drought stress treatment, indicating more accumulation of H2O2 and O\(^-\) in the mlp43-1 mutant (Fig. 5A). We also measured the H2O2 content in the young seedlings, and found that drought stress induced rapid accumulation of H2O2 after 14 d of drought treatment in all genotypes. However, the H2O2 level was significantly higher in the mlp43-1 mutant plants, but lower in MLP43 OE when compared with Col-0 plants (Fig. 5B). Next, the enzymatic activities of SOD and CAT were measured under the same drought conditions. The results indicated that no significant differences of CAT activity were observed among three genotypes after drought treatment for 7 d, however, SOD activities were 1.5-fold higher in MLP43 OE plants than wildtype (Col-0) and the mlp43-1 mutant, respectively (Fig. 5C, D). Moreover, both SOD and CAT activities showed a significant decrease in mlp43-1 and increase in MLP43 OE relative to Col-0 plants after drought treatment for 14 d and 21 d, respectively.

To elucidate the metabolic responses of MLP43 to drought stress treatment, GC-TOF-MS was applied to test whether the primary metabolite profiling was modified by MLP43 overexpression. The results indicated that 34 metabolites including 9 carbohydrates, 9 amino acids, 9 organic acids and 7 other derivatives were reproducibly identified (Fig. 6;
Supplementary Table S5). Compared with wildtype (Col-0), most of the detected metabolites showed <2-fold differences in MLP43 ectopic expression lines without drought treatment. However, the contents of most of the examined carbohydrates and amino acids were significantly decreased in the mlp43-1 mutant, but increased in MLP43 OE transgenic plants after drought treatment (Fig. 6). Except D-(+)-galactose, all carbohydrates, including maltose, sorbose, cellobiose, turanose, glucose, psicose and galactose, decreased in the mlp43-1 mutant but increased in MLP43 OE when compared to Col-0 under the withheld water condition (Fig. 6). A similar change was observed for citrulline, threonine, valine, serine, proline, alanine and lysine, with the exception of glutamine and glycine (Fig. 6). In addition, hexadecanoic acid, galactinol,
myo-inositol and androst-2-en-17-amine increased, while cin-
amic acid, propanoic acid and 2-butenedioic acid decreased
either in mlp43-1 mutants or in MLP43 transgenic plants
under drought treatment conditions.

Transcriptional alterations of ABA- and drought-
responsive genes by MLP43
To further determine the role of MLP43 in the ABA signal-
ing pathway and drought stress responses, we assessed the
expression patterns of genes involved in ABA- and drought-
responsive processes. Two-week-old seedlings were pretreated
with 50 μM ABA for 3 h or air dried for 6 h, respecti-
vely, after which gene expression levels were analysed by qRT-PCR.
We compared the expression levels of several ABA- and/or
abiotic stress-responsive genes, including DREB2A, KIN2,
RAB18, RD20, RD29A and RD29B. All of them showed
extensively increased transcriptional levels after ABA and air-
dry treatments in all three genotypes (Fig. 7). However, the
fold changes of DREB2A, KIN2, RAB18, RD20, RD29A and RD29B were
significantly lower in the mlp43-1 mutant, but higher in the
MLP43 OE plants compared to those in Col-0. ABA treat-
ment significantly enhanced the transcription of above ABA-
and drought-responsive genes in MLP43 OE plants, which
was consistent with the ABA hypersensitivity of MLP43 OE
in seed germination and stomatal aperture responses.
Dehydration stress usually promotes ABA production and
actives ABA signal transduction (Chan, 2012), and our
results substantiate this, with ABA and air-dry treatments
inducing similar expression patterns of the above detected
genes (Fig. 6). In addition, we also examined expression level
changes of three ABA biosynthesis genes, ABA1, ABA2 and
NCED3. The results indicated that there were no significant
differences among the three genotypes after ABA or air-dry
treatments. As MLP43 modulated ROS production, we also
examined the relative expression levels of RbohD and RbohE
encoding NADPH oxidases which promote ROS production
especially after ABA and drought treatment (Torres et al.,
2002; Miller et al., 2010). Results revealed no significant dif-
fences except that RbohE showed a relatively higher expres-
sion level in the presence of ABA (Fig. 7, last panel). Based
on the above results, we concluded that the overexpression of
MLP43 enhanced plant drought stress adaptation through an
ABA-dependent manner.

MLP43 positively modulated ABA responses in reconstituted ABA signalling pathway
To elucidate how MLP43 modulated the expression of down-
stream targets of the ABA signalling pathway, we performed a
transient expression assay in Arabidopsis mesophyll protoplasts
extracted from Col-0 and snrk2.2/2.3/2.6, respectively, using
ProRD29A::LUC as reporter and ProUBQ::GUS as internal
control, and Pro35S::GFP as empty vector control. The results
indicated that transient overexpression of MLP43 significantly
enhanced the transcriptional activity of RD29A promoter after
ABA treatment in Col-0 but not in snrk2.2/2.3/2.6 (Fig. 8A). We
then checked expression patterns of MLP43 in mutants of pri-
mary ABA signalling components, including the
pyr1/pyl1/pyl4 triple mutant (pyr1), ostl-1, abl-1 and the ABA-deficient
mutant aba1-1. When compared with wildtype (Col-0 and Ler), the
expression level of MLP43 was up-regulated in all the exam-
ined mutants, especially in the ABA-deficient mutant aba1-1
with ~3-fold increases at the transcriptional level (Fig. 8B).
In order to gain more clues about the effect of *MLP43* in the ABA signalling pathway, we reconstituted the ABA signalling pathway in wildtype (Col-0) protoplasts (Fig. 8C). As expected, co-transformation of *ABF2* and SnRK2.6 could extensively activate RD29A::LUC activity and PYR1 inhibited ABI1 activity and then enabled expression of the ABA-dependent transcription of RD29A::LUC (Fig. 8C). However, in the presence of *MLP43* overexpression, the activity of RD29A::LUC significantly increased, especially after ABA treatment when compared with empty vector control (Fig. 8C).

We further examined the interactions between *MLP43* and the key ABA signal components. First, the phylogenetic relationships among nine *MLP* homologous genes were analysed based on the full length amino acid sequences (Supplementary Fig. S4). Another two *MLPs* (*MLP34* and *MLP168*), which shared differential homology with *MLP43*, were selected for the yeast two-hybrid assay together with *MLP43*. The results indicated that MLP43 could interact with SnRK2.6 and ABF1 in the yeast two-hybrid assay independent of ABA (Fig. 8D; Supplementary Fig. S5). However, we did not...
detect any interactions between MLP34 or MLP168 and the key ABA signal components, except the interaction between MLP168 and wildtype ABI5 protein (Supplementary Fig. S5A). Interestingly, mutated proteins carrying single or triple phosphoamino acid mutations (S42A, S145A and T201A) in ABI5 could eliminate its interactions with MLP168 (Supplementary Fig. S5A). Taken together, the above results indicated that MLP43 might function as a positive regulator through interacting with SnRK2.6 and ABFs in ABA signalling responses, and ABA could negatively regulate the expression of MLP43 in vivo.

**Discussion**

In this study, the function of MLP43 was characterized during plant stress responses. Both MLP43 and ABA receptors PYL/PYR belong to the Bet v 1 family and share similar protein structure. We speculated that MLP43 might be involved in the ABA signalling pathway. The efficiency of water loss is responsible for plant tolerance to drought stress, and rapid water loss leads to greater drought sensitivity. As indicated, the rosette leaf water loss of the mlp43-1 mutant was significantly more rapid than wildtype (Col-0) under the same drought stress conditions, resulting in higher electrolyte leakage and lower survival rates (Fig. 3). The above results were consistent with ABA insensitivity of mlp43 in seed germination. As we know, ABA and GA₃ antagonistically regulate seed germination (Lee et al., 2002; Piskurewicz et al., 2008). Interestingly, MLP43 expression was significantly inhibited by ABA, but promoted by GA₃ (Fig. 2A). Moreover, drought and salt treatments also negatively regulated MLP43 expression. We also analysed the 1769 bp promoter sequence of MLP43 and found two ACGT-containing ABRE-like elements in the promoter region, located at −1291 bp to −1294 bp and −1088 bp to −1092 bp, respectively. Interestingly, a functional G-box (CACGTG) was also identified in the MLP43 promoter, located at −603 bp to −608 bp close to the ATG start codon of MLP43. The occurrence of both an ABRE and G-box motif in the MLP43 promoter is consistent with previous studies that indicated that ABRE/G-box elements were usually co-recognized by ABA responsive transcription factors (Menkens et al., 1995; Shen and Ho, 1995; Ho et al., 1999).

To further elucidate the mechanism of MLP43 in mediating ABA and drought responses, the comparisons of expression levels of ABA- and drought-responsive genes were performed. As expected, the expression levels of DREB2A,
KIN2, RAB18, RD29A and RD29B were up-regulated by ABA treatment, but showed lower expression levels in mlp43-1 and higher expression levels in MLP43 OE when compared with those in Col-0 after ABA treatment. These results indicated that MLP43 enhanced ABA signal transduction and drought stress tolerance through modulating downstream targets of ABA and drought stress responses. In addition, expression levels of ABA biosynthesis-related genes, such as ABA1, ABA2 and NCED3 showed no significant changes in mlp43 and MLP43 OE lines indicating that MLP43 modulated ABA responses independent of the ABA biosynthesis pathway. However, MLP43 expression was up-regulated in the ABA receptor triple mutant pyr1-1 pyll1/pyl4, as well as in ostl-1, abil-1 (dominant negative mutant) and abal-1 mutants, when compared with those in wildtype Col-0 and Ler (Fig. 8B). In other words, disturbance of ABA signalling transduction or ABA biosynthesis blocked the inhibitory effect of ABA on MLP43 transcription, indicating that the above key ABA signal components are important intermediaries for the negative regulation of ABA on MLP43 expression. Moreover, the re-constituted ABA signal pathway confirmed that transient over-expression of MLP43 in protoplasts enhanced ABA responses by determining the reporter RD29A::LUC activity (Fig. 8C). However, mutation in SnRK2.2/2.3/2.6 eliminated the positive effect of MLP43 on ABA responses in the transient expression assay.
which provides evidence that MLP43 functions up-stream of SnRK2s in the ABA signal pathway (Fig. 8A).

Furthermore, the interactions between MLP43 and SnRK2.6 or ABFs could be detected in the yeast two-hybrid assay (Fig. 8D; Supplementary Fig. S5), which provided direct evidence for the involvement of MLP43 in the ABA signalling pathway. In the core ABA signalling pathway, PYL/PYRs interact with PP2Cs in the present of ABA to form PYL/PP2Cs complexes, which in turn inhibits the activity of the PP2Cs in an ABA-dependent manner, allowing activation of SnRK2s (Ma et al., 2009; Park et al., 2009). To date, no direct interactions between ABA receptors PYL/PPYRs and SnRK2s have been reported. Therefore, even though MLPs and the ABA receptor RCAR/PYR/PYL of Arabidopsis proteins share amino acid and structural similarity at the protein level, MLP43 does not interact with AB1, a key negative regulator of PP2Cs in the ABA signalling pathway. We speculated that MLPs might function as positive ABA regulators through direct regulation of downstream SnRK2s or ABF activities. Solid evidence through the yeast two-hybrid assay verified that MLP43 interacts with SnRK2.6 and ABF1 (Fig. 8D). However, the MLP homologous genes might be functionally diverse in their ABA responses as there were no interactions between MLP34/MLP168 and other ABA signalling components, except that MLP168 could interact with ABI5 in yeast (Supplementary Fig. 5). Presence or absence of ABA had no different effect on the interactions between MLPs and SnRK2/ABFs, indicating the interaction between MLP43 and SnRK2.6 or ABF1 is ABA independent. Therefore, our study provides experimental evidence to elucidate how MLP43 functions as a positive regulator in ABA signalling and drought stress responses.

Accumulating evidence indicates that ABA-enhanced water stress tolerance is associated with induction of antioxidant defence systems, including ROS-scavenging enzymes such as SOD, CAT and APX (Mittler et al., 2011). ROS are small molecules generated during development and in response to stress, and function as eukaryotic intracellular second messengers (Finkel, 1998; Mittler et al., 2011). In Arabidopsis, AtRbohD and AtRbohE encode NADPH oxidases which catalyse NADPH into NADP and ROS especially after ABA and drought treatment (Torres et al., 2002; Kwak et al., 2003; Miller et al., 2010). Our results showed that mutation of MLP43 increased ROS accumulation under drought stress conditions (Fig. 5A), indicating the involvement of MLP43 in ROS-mediated drought responses. However, MLP43 did not modulate RbohD and RbohF transcript levels according to the qRT-PCR results, which indicated that MLP43 preferably regulated ROS scavenging but not production (Fig. 7). The further accumulation of excessive ROS causes more severe oxidative damage to plant cells and stimulates antioxidase activities (Mittler, 2002). SOD and CAT are two important antioxidases that scavenge excessive ROS to prevent cell damage. We determined significant increases of both SOD and CAT activities in MLP43-overexpressed transgenic plants (Fig. 5C, D), which suggests that MLP43 played a role in scavenging the excessive ROS production under dehydration to enhance drought tolerance.

During plant abiotic stress responses, compatible solutes are important in helping plants balance external osmotic pressure and maintain cellular function of macromolecules. In this study, we further examined primary metabolic profiles using GC-TOF MS. The results indicated several carbohydrates and amino acids accumulated in MLP43 plants (Fig. 6). The increased amounts of alanine and glutamic acid in MLP43 OE plants during drought stress treatment might regulate photosynthesis intensity (Bocian et al., 2015). Moreover, overexpression of MLP43 resulted in accumulation of free proline, maltose, trehalose and glucose, which in turn contributed to conferred drought tolerance (Garg et al., 2002). Galactinol has a positive effect in protecting plants from drought stress and oxidative damage (Taiji et al., 2002; Nishizawa et al., 2008). In our study, galactinol showed significant increases after drought treatment, especially in MLP43 OE plants (Fig. 6). Moreover, overexpressed GhMLP led to a two-fold increase in flavonoid contents, which suggested that MLP might be involved in flavonoid metabolism (Chen and Dai, 2010). All these results indicated that MLP43 modulated primary and secondary metabolic profiles, which might be contributed to increased abiotic stress tolerance.

In this study, we dissected the functions of MLP43 in ABA signals and drought stress responses. First, ABA and drought stress treatments inhibited the expression of MLP43, but this inhibition was disturbed in the primary ABA signal components mutants. Second, MLP43 overexpression enhanced ABA responses in seed germination and improved drought stress tolerance by modulating ABA- and/or drought-responsive gene expression, ROS homeostasis and primary metabolic profiling. Third, MLP43 promoted RD29A::LUC activity in the reconstituted ABA signalling pathway, and that was dependent upon SnRK2.2/2.3/2.6. Finally, there were direct interactions between MLP43 and SnRK2.6 or ABF1 in the yeast two-hybrid assay. Collectively, we concluded that MLP43 functioned as a positive regulator upstream of SnRK2s, and ABA down-regulated MLP43 expression as a negative feedback loop, so regulating drought stress responses.

Supplementary data

Supplementary data is available at JXB online.

Supplementary Fig. S1. Phentotypic analysis of another MLP43 T-DNA insertion line mlp43-2 (Salk_033347).

Supplementary Fig. S2. Comparison of primary root length and lateral roots number among Col-0, mlp43-1, MLP OE plants after ABA treatment.

Supplementary Fig. S3. Complementary over-expression of MLP43 into the mlp43-1 mutant (Com-3) showed drought tolerance in soil.

Supplementary Fig. S4. Phylogenetic relationships of nine AtMLP genes.

Supplementary Fig. S5. Yeast two-hybrid assay to detect the interactions between MLP43/MLP34/MLP168 and the key components in the ABA signalling pathway.

Supplementary Table S1. The primers used for identification of the mlp43 mutant (Salk_109337 and Salk_033347).
Supplementary Table S2. Detailed information of plasmid construction in this study.
Supplementary Table S3. The primers used for plasmid construction in this study.
Supplementary Table S4. The primers used for real-time quantitative RT-PCR (qRT-PCR) in this study.
Supplementary Table S5. The detailed list of alterations in metabolite profiling under control and drought treatment in Col-0, mlp43-1 and MLP OE plants.

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