A Chloroplastic UDP-Glucose Pyrophosphorylase from Arabidopsis Is the Committed Enzyme for the First Step of Sulfolipid Biosynthesis

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Plants synthesize a sulfur-containing lipid, sulfoquinovosyldiacylglycerol, which is one of three nonphosphorus glycolipids that provide the bulk of the structural lipids in photosynthetic membranes. Here, the identification of a novel gene, UDP-glucose pyrophosphorylase3 (UGP3), required for sulfolipid biosynthesis is described. Transcriptome coexpression analysis demonstrated highly correlated expression of UGP3 with known genes for sulfolipid biosynthesis in Arabidopsis thaliana. Liquid chromatography–mass spectrometry analysis of leaf lipids in two Arabidopsis ugp3 mutants revealed that no sulfolipid was accumulated in these mutants, indicating the participation of UGP3 in sulfolipid biosynthesis. From the deduced amino acid sequence, UGP3 was presumed to be a UDP-glucose pyrophosphorylase (UGPase) involved in the generation of UDP-glucose, serving as the precursor of the polar head of sulfolipid. Recombinant UGP3 was able to catalyze the formation of UDP-glucose from glucose-1-phosphate and UTP. A transient assay using fluorescence fusion proteins and UGPase activity in isolated chloroplasts indicated chloroplastic localization of UGP3. The transcription level of UGP3 was increased by phosphate starvation. A comparative genomics study on UGP3 homologs across different plant species suggested the structural and functional conservation of the proteins and, thus, a committing role for UGP3 in sulfolipid synthesis.

INTRODUCTION

The photosynthetic membranes of plants are rich in nonphosphorus glycolipids, including galactolipids, mono- and digalactosyldiacylglycerol (MGDG and DGDG), and sulfolipid, sulfoquinovosyldiacylglycerol (SQDG). SQDG is a lipid class that has a unique polar-head constituent, sulfoquinovose, a derivative of glucose in which the 6-hydroxy is replaced by a sulfonate group. SQDG is widely distributed among photosynthetic organisms such as bacteria, cyanobacteria, algae, mosses, ferns, and higher plants (Haines, 1973). The exact role of SQDG under normal growth conditions is still obscure. Mutants of photosynthetic bacteria, Arabidopsis thaliana, and Chlamydomonas reinhardtii completely lacking this lipid show only subtle impairments in photosynthesis and growth unless they are phosphate starved (Benning et al., 1993; Güler et al., 1996; Yu et al., 2002; Riekhof et al., 2003). In photosynthetic organisms, the relative amount of total anionic thylakoid lipids is typically maintained by reciprocally adjusting the contents of SQDG and phosphatidylglycerol (PG) as phosphate availability changes. Typically, the relative content of PG decreases and that of SQDG increases following phosphate limitation (Essigmann et al., 1998; HärTEL et al., 2000; Yu et al., 2002). In SQDG-deficient mutants, the proportion of PG does not decrease under phosphate limitation, and these mutants become phosphate starved sooner than their respective wild types (Benning et al., 1993; Güler et al., 1996; Yu et al., 2002; Riekhof et al., 2003). These observations suggest that one of the main functions of SQDG is to substitute for PG under phosphate limitation to maintain the proper balance of anionic charge in the thylakoid membrane (Benning et al., 1993; Güler et al., 1996; Yu et al., 2002, 2003). Recently, SQDG was reported to be used as a significant internal sulfur source for protein biosynthesis in an early phase of sulfur starvation in C. reinhardtii (Sugimoto et al., 2007). SQDG is one of the primary sulfur-containing organic compounds in higher plants, but it remains unclear whether it plays the same role in higher plants as observed in C. reinhardtii.

In Arabidopsis, SQDG is synthesized in two unique steps (Figure 1): the assembly of UDP-glucose (UDP-Glc) and sulfite into UDP-sulfoquinovose (UDP-SQ) by UDP-sulfoquinovose
synthase SQD1 (Essigmann et al., 1998; Sanda et al., 2001), and the subsequent transfer of sulfoquinovose from UDP-SQ to diacylglycerol for synthesis of the final product by SQDG synthase SQD2 (Yu et al., 2002). These two specific reactions have been determined to occur in chloroplasts based on feeding experiments of isolated chloroplasts with $^{35}$S-labeled sulfate, which revealed that chloroplasts were fully capable of synthesizing SQDG from labeled sulfate (Haas et al., 1980; Kleppinger-Sparace et al., 1985; Joyard et al., 1986; Kleppinger-Sparace and Mudd, 1987, 1990; Pugh et al., 1995) and based on enzyme activities of SQD1 and SQD2 in the chloroplasts (Heinz et al., 1989; Seifert and Heinz, 1992; Tietje and Heinz, 1998; Shimojima et al., 2005). Recombinant SQD1 proteins have been shown to have UDP-SQ synthase activity (Essigmann et al., 1998; Shimojima and Benning, 2003), and the crystal structure of the Arabidopsis SQD1 protein and detailed possible reaction mechanism have been reported (Mulichak et al., 1999; Essigmann et al., 1999). In addition, analysis of SQD1 purified from leaves of spinach (Spinacia oleracea) suggested that native SQD1 interacted with ferredoxin-dependent glutamate synthase to form a large protein complex in the stroma of plants (Shimojima et al., 2005).

Although SQD1 and SQD2 have been characterized at genetic and enzymatic levels, the mechanism of supply of UDP-Glc for the SQDG biosynthetic pathway remains to be addressed. In plants, SQD1 is localized in the stroma of chloroplasts and uses UDP-Glc as a substrate, raising the question of the source of the UDP-Glc. The concentration of UDP-Glc in the chloroplasts is considered to be very low (Bligny et al., 1990). There have been two models developed as possible answers to this question: (1) UDP-Glc is imported into the chloroplasts from the cytosol; (2) UDP-Glc is generated inside the chloroplasts (Benning, 2007).

Along with the massive accumulation of microarray data sets, transcriptome coexpression analysis has proven to be a powerful tool for identifying regulatory relationships in the transcriptional networks of model organisms, including Escherichia coli (Balázs et al., 2005) and yeast (Ihmels et al., 2004). A set of genes involved in a particular biological process (more practically, in a particular metabolic pathway) are often coexpressed under the control of a shared regulatory system. Therefore, if an unknown gene is coexpressed with known genes of a particular metabolic pathway, this unknown gene is probably involved in the pathway (Saito et al., 2008). Based on this concept, new metabolic genes have been identified in Arabidopsis by transcriptome coexpression analysis (Persson et al., 2005; Tohge et al., 2005; Yonekura-Sakakibara et al., 2007, 2008; Hirai et al., 2007).

In this study, a novel gene involved in SQDG biosynthesis in Arabidopsis was identified. Using transcriptome coexpression analysis, we prioritized a previously uncharacterized gene highly coexpressed with known SQDG biosynthetic genes. Lipid profiling of knockout mutants of this gene and an enzyme assay for recombinant protein confirmed that this gene encodes UDP-glucose pyrophosphorylase (UGPase) involved in the supply of UDP-Glc to the chloroplasts requisite for SQDG biosynthesis. The mechanism, regulation, and evolution of SQDG biosynthesis were further clarified.

**RESULTS**

An Uncharacterized Gene UGP3 (At3g56040) Is Highly Coexpressed with Genes Involved in SQDG Biosynthesis

To identify novel genes involved in lipid metabolism, coexpression analyses were conducted within the ATTED-II database using a coexpression gene search program on the RIKEN PRIME website (Obayashi et al., 2007; Akiyama et al., 2008). Based on

![Figure 1. The Sulfolipid Biosynthesis Pathway in Arabidopsis.](image-url)
the concept that a set of genes involved in a biological process are co-regulated under the control of a shared regulatory system, the coexpression pattern of genes involved in the metabolism of polar glycerolipids in plastids was analyzed. Coexpression relationships were visualized as a graph, in which a pair of genes (two vertices) with a high correlation coefficient (>0.50) is connected by a line (Figure 2). Four known genes (SQD1, SQD2, MGD2, and MGD3) involved in sulfolipid and galactolipid biosynthetic pathways are clustered in the same group, suggesting a shared regulatory system for these pathways. Genes that coexpressed with at least two of these four genes were selected based on their correlation coefficient (>0.50 with all conditions), considering annotations for gene functions. These analyses revealed that an unknown gene, At3g56040, and two genes coding putative lipases (At1g08310 and At2g42690) were coexpressed with SQD1, SQD2, MGD2, and MGD3 in sulfolipid and galactolipid biosynthetic pathways. Genes that coexpressed with at least two of these four genes were selected based on their correlation coefficient (>0.50 with all conditions), considering annotations for gene functions. These analyses revealed that an unknown gene, At3g56040, and two genes coding putative lipases (At1g08310 and At2g42690) were coexpressed with SQD1, SQD2, MGD2, and MGD3 (Figure 2), suggesting the involvement of these genes in the biosynthesis of SQDG or galactolipid. In particular, At3g56040, coexpressing with SQD1 and SQD2, was predicted to be involved in SQDG synthesis, although this gene is annotated only as a gene coding an expressed protein. From this point, this gene will be referred to as UGP3, since in the following sections the product of this gene is demonstrated to exhibit UGPase activity, and two UGPase genes, UGP1 and UGP2, have been reported previously (Meng et al., 2008). The prediction that UGP3 was involved in SQDG biosynthesis was reinforced by examining the tissue-specific expression patterns of transcripts of UGP3, SQD1, and SQD2; Arabidopsis eFP- Browser (Winter et al., 2007) showed that these three genes are coordinately expressed in leaves, stems, and flowers (see Supplemental Figure 1 online), thus supporting the close relationship among these genes. The transcript levels of UGP3 were upregulated by phosphate limitation, as reported for SQD1 and SQD2 (Essigmann et al., 1998; Yu et al., 2002), as shown by an analysis using Genevestigator (Zimmermann et al., 2005) (see Supplemental Figure 2 online). These results of gene expression analyses support the hypothesis that UGP3 is involved in SQDG biosynthesis.

Two ugp3 Mutants Are Completely Devoid of SQDG
To examine the function of UGP3 in vivo, two independent T-DNA insertion lines obtained from the SALK collection were investigated (Alonso et al., 2003). Sequence analysis of the flanking regions of the T-DNA revealed that the T-DNA insertion sites of SALK_020654 (designated as ugp3-1) and SALK_073806 (designated as ugp3-2) were located in exon 1 (75 bp downstream from the ATG) and exon 15 (4340 bp downstream from the ATG), respectively (see Supplemental Figure 3A online). No transcripts of UGP3 were detected using RT-PCR in the homozygotes of either mutant line (see Supplemental Figure 3B online), and there were no obvious phenotypic abnormalities in the mutant plants.

Crude lipid fractions were extracted from the rosette leaves of wild-type plants and two ugp3 mutants and subjected to liquid chromatography/ion trap time-of-flight mass spectrometry (LC-IT-TOF-MS). Chromatographic separations were performed using hydrophilic interaction chromatography based on the interactions between the polar moieties of the stationary phase and the analytes. Thus, the separation mode is almost same as that of normal phase chromatography on silica gels, and lipid molecules were separated based on their polar moieties. The major SQDG species in the leaves of wild-type Arabidopsis observed with negative electrospray ionization (ESI)-MS were the same as reported previously (Welti et al., 2003) (see Supplemental Figure 4A online). The structure of the polar headgroup was also confirmed by MS/MS spectra that displayed the ions specific to sulfoquinovose moiety as reported (Welti et al., 2003) (see Supplemental Figures 4B and 4C online). Based on these data, the accumulation patterns of SQDG in the leaves of wild-type plants and two ugp3 mutants were analyzed by comparing the intensities of the extracted ion chromatograms of the [M-H]⁻ species of SQDG (see Supplemental Figure 5 online). No accumulation of SQDG was observed in either the ugp3-1 or ugp3-2 mutant. These results indicate that SQDG biosynthesis was completely inactivated in the two ugp3 mutants. Profiles of polar glycerolipids, including SQDG, were compared for lipid extracts.
from leaves of wild-type plants and ugp3 mutants (Figure 3). No remarkable changes in the amounts of specific lipid species were observed except for SQDG, although slight but statistically significant increases in several molecular species of PG (34:3 and 34:4 PG) and phosphatidylinositol (34:3 PI) were observed. To investigate wide-ranging alteration of metabolites, untargeted analyses using LC-IT-TOF-MS for other lipids and using ultra-performance liquid chromatography (UPLC)-Q-TOF-MS for more general hydrophilic metabolites were also performed. However, no significant changes were observed except in the amounts of SQDG, indicating the specific involvement of UGP3 in SQDG biosynthesis (see Supplemental Figures 6 and 7 online).

Figure 3. Profiles of Polar Glycerolipids in Leaves of the Wild Type and ugp3 Mutants.

Peak areas of individual lipid molecules were determined by monitoring their molecular-related ions or fragment ions (see Methods). Levels of individual lipid molecules in the wild type and mutant lines were expressed as relative values against the sum of the peak areas of lipid molecules with the same polar headgroups in the wild type. For example, in the case of 34:6 MGDG in ugp3-1, \((\text{peak area of 34:6 MGDG molecule in 34:6 MGDG)/(total area of all MGDG species in the wild type)}) \times 100\) was expressed as the height of the bar. Each data point expresses the mean of eight experiments \(\pm\) SD. Asterisks indicate a statistically significant difference from the wild type \((P < 0.05, **P < 0.01, \text{Student's t test})\). PC, phosphatidylcholine; PE, phosphatidylethanolamine.
Analysis of the Amino Acid Sequence of UGP3 Suggests That UGP3 Encodes UGPase

The protein corresponding to the UGP3 gene contains 883 amino acids and a predicted chloroplast-targeting peptide of 72 amino acids at the N-terminus (ChloroP; Emanuelsson et al., 1999), thereby suggesting that the UGP3 protein is localized in the chloroplasts. The amino acid sequence of UGP3 has a homology with those of grape (Vitis vinifera) (GSVIVP00023934001), rice (Oryza sativa) (Os05g0468600), C. reinhardtii (AY310119, LPB1), Ostreococcus tauri (CAL56361), and the gram-negative bacterium Candidatus Protochloramydia amoebophila UWE25 (YP_007323) previously referred to as Parachlamydia-related strain UWE25, with an identity of 64, 54, 45, 45, and 39%, respectively, forming a distinct subfamily (Figure 4A; see Supplemental Figure 8 online). All of these proteins are annotated as unknown proteins except LPB1 from C. reinhardtii. The lpb1 mutant of C. reinhardtii was reported to die more rapidly than the wild type during phosphorus and sulfur limitation (Chang et al., 2005), but its function has not been determined at a biochemical level. The sequence of UGP3 also shares low but significant identities with UDP-sugar pyrophosphorylase (USPase) from Cucumis melo (ABDS9006; 22%) and Pisum sativum (Q5W915; 22%), which accept a wide range of hexose 1-phosphates as substrates, at the amino acid level. The polypeptide of UGP3 contains a putative pyrophosphorylase consensus motif and a nucleotide binding motif (Figure 4B). These structural features of the protein sequence suggest that the UGP3 protein is a chloroplast-localized UGPase for the generation of UDP-Glc from glucose-1-phosphate and UTP. As shown in Figure 4A, the proteins categorized in the subfamily containing UGP3, provisionally designated as type B UGPases, are distinct from the previously characterized subfamilies UDP-N-acetylglucosamine pyrophosphorylases, USPases, and another type of UGPases provisionally donated as type A UGPases, consisting of many reported UGPases.

Recombinant UGP3 Exhibits UGPase Activity

Recombinant UGP3 protein, which lacks putative chloroplastic transit peptides (72 residues) at the N-terminus, was expressed in E. coli (see Supplemental Figure 9 online). UGPase activity was examined for the forward reaction (synthesis of UDP-Glc). The enzyme reaction product was subjected to UPLC-Q-MS analysis. The recombinant UGP3 protein catalyzed the formation of UDP-Glc from [1-13C]glucose-1-phosphate (Glc1P) and UTP, as confirmed by comparing its chromatographic behavior on liquid chromatography and its mass spectrum with those of the standard compound (Figure 5; see Supplemental Figure 10 online). These two experiments indicate that the UGP3 enzyme activity of the recombinant UGP3 was localized in the chloroplasts from the Arabidopsis (Kotake et al., 2004, 2007; Litterer et al., 2006).

Many UDP-hexose pyrophosphorylases have been reported to require the divalent cation Mg2+ for activity. To examine its requirement for Mg2+ for activity, the UGPase activity of UGP3 was measured at various concentrations of Mg2+ (0.1 to 30 mM). The enzyme showed an absolute requirement for the divalent cation Mg2+ for activity (Table 2). Enzyme activity was found to be almost equilibrated in the range of 5 to 10 mM of Mg2+. These results are consistent with previous studies on USPases from humans, Acanthamoeba castellanii, and potato (Solanum tuberosum) (Tsuboi et al., 1969; Rudick and Weisman, 1974; Nakano et al., 1989) and USPases from pea and Arabidopsis (Kotake et al., 2004, 2007), in which the MgUTP complex was postulated to be the actual substrate for the UGPases. The effect of pyrophosphate on the UGPase activity of the recombinant UGP3 was examined. Addition of pyrophosphate strongly inhibited the UGPase activity of the recombinant UGP3 (Table 3), as has been reported for other UGPases and USPases (Tsuboi et al., 1969; Rudick and Weisman, 1974; Nakano et al., 1989; Kotake et al., 2004, 2007) because of the product inhibition mechanism.

UGP3 Is Located in the Chloroplasts

To confirm the chloroplastic targeting of UGP3, the N-terminal 200 amino acids, including the predicted chloroplastic transit peptide (cTP) of UGP3, were fused to the yellow fluorescent protein (YFP) reporter gene (Figure 6A) and subsequently used to transiently transform Arabidopsis cells. Figure 6B shows that the fluorescence derived from YFP was associated with the chloroplasts, which were identified by the red autofluorescence of their chlorophylls. Transient expression of SQD1 and UGP3, which were C-terminally fused with the green fluorescent protein (GFP) reporter gene in onion epidermal cells, also showed that both SQD1 and UGP3 were targeted to the plastids (see Supplemental Figure 11 online). These two experiments indicate that UGP3 is a chloroplast-localized protein.

UGPase Activity Is Severely Diminished in Chloroplasts in ugp3 Mutants

Intact chloroplasts were isolated from leaves of wild-type plants and ugp3 mutants, and the UGPase activity in isolated chloroplasts was measured (see Supplemental Figure 12 online). A severe decrease (~50%) in UGPase activity was observed in chloroplasts from the ugp3 mutants compared with the wild type, suggesting that UGP3 is responsible for a majority of the UGPase activity in chloroplasts. However, substantial activity was still
Contamination of the chloroplastic fraction by proteins from the cytosol was checked by measuring the activity of cytosolic marker protein, alcohol dehydrogenase (ADH), because plants are supposed to have substantial UGPase activity in the cytosol (Kleczkowski et al., 2004). On the basis of the ADH activities in the enzyme extracts from whole leaves and chloroplastic fractions, the respective amounts of UGPase activity attributable to cytosolic proteins were estimated to be 7, 14, and 13% of the UGPase activities in the chloroplastic fractions from the wild type, ugp3-1, and ugp3-2, indicating that protein contamination from the cytosol could not explain the decrease of UGPase activity in the chloroplast fraction of ugp3 mutants. UGPase activities in whole leaves of the wild type, ugp3-1, and ugp3-2 were determined to be 56.5 ± 4.6, 48.1 ± 7.3, and 51.5 ± 5.7 (pkatal g⁻¹ fresh weight), respectively. Levels of UDP-Glc in whole leaves of the wild type, ugp3-1, and ugp3-2 were...
determined to be 57.8 ± 3.8, 63.6 ± 5.4, and 59.3 ± 4.3 (µg g⁻¹ fresh weight), respectively. These results indicate that the total levels of UGPase activity and UDP-Glc in leaves are only slightly affected by knockout of the UGP3 gene.

The Effects of Phosphate and Sulfate Starvation on Lipid Composition

Phosphate deprivation is known to induce an increase in levels of SQDG in the leaves of Arabidopsis to compensate for the decrease in phospholipids, especially PG, through activation of expression of SQD1 and SQD2 (Essigmann et al., 1998; Yu et al., 2002). Based on the results of gene expression analysis shown in Supplemental Figure 2 online, it was expected that the expression of the UGP3 gene would be elevated by phosphate limitation along with SQD1 and SQD2. As expected, quantitative PCR revealed that the expression of the UGP3 gene was increased almost 15-fold by phosphate limitation compared with that under phosphate-sufficient growth conditions (see Supplemental Figure 13 online). To investigate the effects of lack of SQDG on lipid metabolism in the ugp3 mutants under phosphate-limiting conditions, polar glycerolipid composition was compared in extracts from leaves of wild-type plants and ugp3 mutants grown in the presence and absence of phosphate. In addition, another SQDG-deficient mutant of Arabidopsis, sqd1, was also subjected to the phosphate starvation experiment to reveal the physiological function of UGP3 in lipid metabolism in detail. The mutants ugp3 and sqd1, deficient in SQDG, accumulated slightly more PG compared with the wild type under phosphate-sufficient growth conditions (Figure 7A). Under phosphate-limiting conditions, the relative amount of SQDG increased by approximately fourfold, and PG amounts decreased by half in the wild type, while SQDG was not detected and PG only slightly decreased in ugp3 and sqd1 mutants. Phosphorus limitation also caused a decrease in other phospholipids (PE and PC) and an increase in DGDG in the wild type, ugp3, and sqd1, but the amounts of decrease and increase in these lipid classes were similar among the wild type, ugp3, and sqd1.

Because SQDG contains sulfur in the polar headgroup, the effect of sulfur limitation on the profiles of polar glycerolipids was also examined. The expression level of UGP3 in leaves of wild-type plants grown under sulfate-depleted conditions for 2 d was about half of that under sulfate-sufficient growth conditions (see Supplemental Figure 13 online). However, sulfur limitation did not necessarily lead to a significant decrease in the relative level of SQDG in the wild type (Figure 7B). In addition, the contents of other polar glycerolipids in the wild type were not as significantly affected by this short-duration sulfur limitation.

UGP3 Homologs Are Evolutionally Conserved across Plant Species

UGP3 homologs are found in several plant species (Figure 4A), suggesting that these proteins are evolutionally conserved across plant species. To determine the evolutionary relationship among UGP3 homologs, a comparative genomics study was...
performed on UGP3 homologs in four higher plant species (Arabidopsis, Populus trichocarpa, V. vinifera, and O. sativa) for which whole-genome sequences are available. All of these species possess UGP3 homologs as a single-copy gene (Figure 8A). The UGP3 homologs found in these species are highly divided by introns (Figure 8A), but the number and size distribution of exons within the coding sequences are highly conserved in these species (Figure 8B) and the genome region coding two important motifs for UGPase activity, pyrophosphorylase consensus and nucleotide binding motifs, are found in the corresponding exons. In addition, all of the UGP3 homologs from these four plant species have been shown to have a putative region coding chloroplastic transit peptides at the first exons, as determined by TargetP. The syntenic relationships among the UGP3 homologs across the four plant species were also analyzed using the Plant Gene Duplication Database (PGDD; http://chibba.agtec.uga.edu/duplication/), which revealed cross-genome syntenic relationships among Ath:At3g56040, Ptr:LPB1, Pop:LPB1, and Vv:GvIPV00029334001 (Figure 8A; see Supplemental Figure 14 online). These studies suggest a close evolutionary relationship and a shared function of the UGP3 homologs in higher plants.

The orthologs of UGP3 homologs also can be found in the genomes of lower plants, Selaginella moellendorffii and C. reinhardtii. In addition, the genomic region and EST homologous to the sequence of UGP3 homologs in lower plants, has 18 genes in S. moellendorffii and C. reinhardtii. In the corresponding full-length sequences of transcripts and amino acids are not available (see Supplemental Figure 15 online). The exon-intron structures of the genes in S. moellendorffii and C. reinhardtii were analyzed and compared with those of higher plants (see Supplemental Figure 16 online). The putative homolog in S. moellendorffii has 18 exons divided by relatively short introns (see Supplemental Figure 16A online), but the number and size distribution of exons within the coding sequences are very similar with those of higher plants (see Supplemental Figure 16B online). The putative homolog in C. reinhardtii (LPB1) has a much smaller number of exons that are differently organized compared with other plants (see Supplemental Figure 16 online). These indicated that the higher plants inherited the basic genomic structure of type B UGPases from ferns, and the structures of introns have diverged through the evolution of higher plants.

Table 2. Effect of Magnesium Ion on UGPase Activity of UGP3

| Mg2+ (mM) | Relative Activity (%) |
|-----------|-----------------------|
| 0.00      | 100                   |
| 0.25      | 98 ± 4.0              |
| 0.50      | 90 ± 7.0              |
| 1.00      | 51 ± 11.0             |
| 0.5       | 38 ± 11.0             |
| 0.1       | 38 ± 11.0             |
| 0.0       | n.d.                  |

Activities of recombinant UGP3 were assayed in the presence of UTP (0.5 mM), [1-13C]Glc1P (0.5 mM), and various amounts of MgCl2. Relative activities are expressed as a percentage of that obtained in the presence of 30 mM MgCl2. n.d., not detected.

DISCUSSION

Transcriptome Coexpression Analysis Efficiently Extracts Coordinately Expressed Genes Involved in Glycoglycerolipid Biosynthesis

SQDG serves to maintain the proper balance of anionic charge in the thylakoid membrane, especially under phosphate-limiting conditions, and thus is considered to be of conditional importance in plants. In this study, an unknown gene involved in SQDG biosynthesis was efficiently targeted using transcriptome coexpression analysis, and its function was determined using a combination of reverse genetics, reverse biochemistry, and detailed lipid profiling. Transcriptome coexpression analysis also showed that MGD2 and MGD3, not involved in SQDG biosynthesis, were grouped into the same cluster with SQDG biosynthetic genes (Figure 2). MGD1, MGD2, and MGD3 encode 1,2-diacylglycerol 3-β-galactosyltransferases, the final enzymes for MGDG synthesis. Among these genes, only MGD1 is highly expressed in all tissues of Arabidopsis, whereas expression of MGD2 and MGD3 are observed only in restricted parts, such as leaf tips and pollen grains (Kobayashi et al., 2004). These tissue-specific expression patterns of MGD2/3 are not that similar to those of SQDG biosynthesis, although the corresponding full-length sequences of transcripts and amino acids are not available (see Supplemental Figure 15 online). The exon-intron structures of the genes in S. moellendorffii and C. reinhardtii were analyzed and compared with those of higher plants (see Supplemental Figure 16 online). The putative homolog in S. moellendorffii has 18 exons divided by relatively short introns (see Supplemental Figure 16A online), but the number and size distribution of exons within the coding sequences are very similar with those of higher plants (see Supplemental Figure 16B online). The putative homolog in C. reinhardtii (LPB1) has a much smaller number of exons that are differently organized compared with other plants (see Supplemental Figure 16 online). These indicated that the higher plants inherited the basic genomic structure of type B UGPases from ferns, and the structures of introns have diverged through the evolution of higher plants.

Table 3. Effect of Pyrophosphate on UGPase Activity of UGP3

| Pyrophosphate (mM) | Relative Activity (%) |
|--------------------|-----------------------|
| 0.00               | 100                   |
| 0.25               | 57 ± 8.4              |
| 0.50               | 19 ± 5.4              |
| 1.00               | 11 ± 6.2              |
| 5.00               | 3.2 ± 2.2             |
| 10.00              | 1.5 ± 1.2             |

Activities of recombinant UGP3 were assayed in the presence of UTP (0.5 mM), [1-13C]Glc1P (0.5 mM), and various amounts of sodium pyrophosphate. Relative activities are expressed as percentages of that obtained without addition of pyrophosphate.
UDP-Glc for SQDG Synthesis Is Generated inside Chloroplasts by UGP3

UDP-galactose, a precursor of galactolipids synthesized in chloroplasts, is widely assumed to be incorporated from the cytosol (Benning and Ohta, 2005) because the concentration of UDP-galactose is very low inside plastids and high in the cytosol (Bligny et al., 1990) and because MGDG synthase, MGD1, is located on the outside of the inner chloroplastic envelope membrane (Xu et al., 2005). UDP-Glc for SQDG biosynthesis has also been speculated to be of cytosolic origin, and certain proteins have been proposed as the candidate transporters of UDP-Glc into the chloroplasts. To understand the origin of the residual UDP-Glc for SQDG synthesis, we investigated whether UDP-Glc for SQDG synthesis is generated inside the chloroplasts, as is UGP3. In this case, UDP-Glc generated by UGP3 should be specifically supplied for SQDG1, presumably through a substrate channeling mechanism or sub-organelle compartmentation. There is also the possibility that certain cytosolic UDP-hexose pyrophosphorylases might be bound to the surface of the chloroplasts but are not found inside the chloroplasts. To understand the origin of the residual UDP-Glc for SQDG synthesis in isolated chloroplastic fractions of ugp3 mutants, further studies of other possible UDP-hexose pyrophosphorylases would be required.

Knockout of the UGP3 Gene Causes Compositional Changes of Anionic Lipids in Chloroplasts and Conditionally Affects the Biosynthesis of Galactolipid

Slight increases in the amount of PG were observed in ugp3 mutants compared with the wild type under normal growth conditions (Figures 3 and 7). Under phosphate-limiting conditions, the relative amount of SQDG increased and the amount of PG decreased in the wild type, whereas SQDG was not detected and PG barely decreased in the ugp3 and sqd1 mutants (Figure 7). These results are consistent with previous reports on the sqd2 mutant and support the theory that the amounts of SQDG and PG are reciprocally controlled in plants to maintain the proper balance of anionic charge in the thylakoid membrane (Benning et al., 1993; Güler et al., 1996; Yu et al., 2002, 2003).

In addition to these changes in lipid accumulation patterns in ugp3 mutants, also observed in sqd2 (Yu et al., 2002), the relative amount of MGDG seemed to slightly decrease in the ugp3 mutant compared with the wild type under phosphate-sufficient growth conditions (Figure 7). Although the sqd1 mutant lacked SQDG, as did ugp3, the relative amount of MGDG in sqd1 was similar to that of the wild type under phosphate-sufficient and phosphate-limiting conditions. These results suggest that knockout of the UGP3 gene has a slight effect on MGDG biosynthesis in a condition-dependent manner.
UDP-Glc is an important metabolite used for synthesis of various kinds of glycosides and saccharides. To reveal the function of UGP3 in more detail, methanolic extracts of rosette leaves were subjected to untargeted reversed-phase LC-MS analysis. Methanolic extracts of Arabidopsis leaves contain glycosides, such as flavonoids and glucosinolates, and compounds synthesized from glycosylated precursors, such as sinapoylmalate. The amounts of these compounds were nearly the same between the wild type and ugp3 mutants, and no significant changes in the amounts of specific metabolites could be found between the wild type and ugp3 mutants (see Supplementary Figure 7 online). These data suggest that UDP-Glc for biosynthesis of secondary metabolites and cellulose can be sufficiently supplied by other UGPases, such as UGP1 and UGP2, which are thought to be localized in the cytosol in Arabidopsis (Meng et al., 2008).

UGP3 and Its Homologs Are Unique UGPases Found in Plants

Phylogenetic analysis revealed that UGP3 belongs to a novel protein family, type B UGPases, with biochemically uncharacterized proteins from the higher plants (V. vinifera, P. trichocarpa, and O. sativa) and two unicellular green algae (O. tauri and C.
reinhardtii) as close homologs (Figures 4 and 8), which likely exhibit substrate specificity similar to that of UGP3 in Arabidopsis. UGP3 exhibited a high specificity for Glc1P, followed by Gal1P as glycosyl donor (Table 1). At the amino acid level, the most closely related proteins to type B UGPases are USPases, which catalyze the conversion of various monosaccharide-1-phosphates to their respective UDP-sugars (Figure 4) (Kotake et al., 2004, 2007; Litterer et al., 2006). The property that UGP3 accepts Gal1P as a poor substrate may be related to the sequence similarity with USPases.

Figure 8. Evolutional Studies of the UGP3 Homologs in Higher Plants.

(A) Left: Phylogenetic relationships of the UGP3 proteins in higher plants. The unrooted phylogenetic tree was constructed by alignment of deduced amino acid sequences from Arabidopsis (Ath), P. trichocarpa (Ptr), V. vinifera (Vvi), and O. sativa (Osa). The bar indicates substitutions per site. Bootstrap values (1000 replicates) are shown on branches. Dashed arrows indicate gene pairs in terms of cross-genome syntenic relationships. Right: Exon-intron structures of the UGP3 genes. The untranslated region (UTR) sequences are shown when available. Open boxes represent UTRs; solid boxes, coding regions; and solid lines, introns.

(B) The number and size distribution of exons within the coding sequences of UGP3 homologs.

Figure 9. Proposed Biosynthetic Pathway for Sulfolipid and Galactolipids in Chloroplasts.

Biosynthetic schemes for three glycoglycerolipids under normal growth conditions are illustrated along with the pathway involving UGP3.
Comparative genomics analysis of UGP3 homologs revealed the conservation of gene structures and cross-genomic syntenic relationships in several model plants, suggesting a close evolutionary relationship and a shared function of UGP3 homologs in higher plants (Figure 8; see Supplemental Figure 16 online). Arabidopsis has another type of UGPase family proteins, UGP1 and UGP2, which can catalyze the formation of UDP-Glc as can UGP3. To investigate the distributions of these UGPases, homologs of type A UGPases were investigated in four plant species (Arabidopsis, P. trichocarpa, V. vinifera, and O. sativa) as UGP3 homologs. All of these four plant species have one or two genes coding type A UGPase homologs (see Supplemental Figure 17 online). These results suggest that plants possess two different types of UGPases, and the presence of each subfamily, conserved throughout plant evolution, could be profitable for metabolism of UDP-sugars in plants.

LPB1 of C. reinhardtii is one of the close homologs of UGP3, and the only one of these proteins whose function has been investigated (Chang et al., 2005). The lpb1 mutant was reported to die more rapidly than the wild type under phosphorus and sulfate limitation. If LPB1 has the same physiological function as UGP3 in C. reinhardtii, the amount of SQDG in lpb1 might be decreased compared with the wild type. There are common visible phenotypes observed in lpb1 and a SQDG-deficient mutant of C. reinhardtii, Δsqd1 (Riekhof et al., 2003). The growth of both mutants ceases faster than the wild type under phosphate-depleted conditions. In addition, both mutants are more sensitive to 3-(3,4-dichlorophenyl)-1,1-dimethylurea (DCMU), a herbicide binding to the Qb acceptor site of photosystem II, than the wild type, suggesting changes in the chemistry of photosystem II. Another SQDG-deficient mutant of C. reinhardtii, hf-2, also shows enhanced sensitivity to DCMU compared with the wild type, although the exact molecular defect is not known (Sato et al., 1995; Minoda et al., 2002). Since C. reinhardtii is apparently a distinct organism from Arabidopsis, LPB1 may also have quite different physiological functions from UGP3. In contrast with lpb1, ugp3 mutants of Arabidopsis did not show as severe growth defects compared with the wild type when they were grown under phosphate- and sulfate-limiting conditions. As described by Chang et al. (2005), LPB1 may play a role in some aspect of polysaccharide metabolism and/or influence phosphorus metabolism (either structural or regulatory) in a way that is critical for allowing the cells to acclimate to nutrient-deficient conditions.

Orthologs of Three SQDG Biosynthetic Genes Are Differently Distributed among Organisms

Orthologs of SQD1 and SQD2 of Arabidopsis can be found in cyanobacteria, which are thought to be closely related to the ancestral bacteria of chloroplasts (Essigmann et al., 1998; Yu et al., 2002). Therefore, it was expected that orthologs of UGP3 in Arabidopsis could also be found in cyanobacteria. However, a counterpart for UGP3 was not found in cyanobacteria. Thus, UDP-Glc for SQDG is synthesized or supplied for UDP-SQ synthase by a different mechanism in cyanobacteria. In comparison to the case of cyanobacteria, a homologous protein sequence was found in Candidatus Protochlamydia amoebophila UWE25. UWE25 is an endosymbiotic chlamydial species that is thought to have diverged from the Chlamydiaceae ~700 million years ago. A number of putative plant genes with significant similarity to UWE25 have been localized to the chloroplast, suggesting their involvement in the development of endosymbiosis of a cyanobacterium in Plantae ancestry (Horn et al., 2004; Moustafa et al., 2008). In contrast with UGP3, sequences homologous to SQD1 and SQD2 are not found in UWE25. These results suggest that the SQDG biosynthetic pathway in plants is not simply inherited from cyanobacteria. Most likely, a symbiotic chlamydia-like cell provided an ancient UGP3 gene to a Plantae ancestor by horizontal gene transfer, and the host cell gradually developed a new regulated metabolic connection between the newly established endosymbiont (cyanobacterium) and the host cell.

UGP3 and Two Other SQDG Biosynthetic Genes Are Differentially Regulated in Arabidopsis Starved for Sulfate

In addition to being a constituent of the lipid bilayer of thylakoid, SQDG is presumed to play a sulfur storage role as one of the major sulfur-containing organic compounds in higher plants. Sulfite generated via the sulfur assimilation pathway is directly incorporated into UDP-SQ (Leustek and Saito, 1999; Saito, 2004). In this study, the amount of SQDG in leaves did not markedly decrease when the plants were grown under sulfur-limiting conditions for 2 d. However, sulfur limitation for a longer time has been reported to lead to a decrease in SQDG in the leaves of Arabidopsis to conserve the sulfur in plants (Nikiforova et al., 2005). To understand the regulation of the genes involved in the SQDG biosynthetic pathway under sulfur-limiting conditions, changes in the expression levels of SQD1, SQD2, and UGP3 in response to sulfur deprivation were analyzed based on transcriptome data provided by the AtGenExpress Visualization Tool (Schmid et al., 2005). As observed in this study, sulfur limitation induced a decrease in the expression of UGP3 compared with sulfur-sufficient conditions, while the expression of SQD1 and SQD2 was hardly affected, at least during the first 24 h after transfer of the Arabidopsis plants to a sulfur-depleted medium (see Supplemental Figure 18 online). These data suggest that the expression of UGP3 is more strictly controlled than the other two SQDG biosynthetic genes when Arabidopsis is transferred to a sulfur-depleted medium, perhaps to reduce the supply of UDP-Glc for SQDG biosynthesis. Downregulation of the gene involved in the farthest upstream reaction step specific to SQDG biosynthesis is reasonable in terms of saving sulfur and carbohydrates.

As described above, UGP3 and the other two SQDG biosynthetic genes in Arabidopsis are likely to be differentially regulated under sulfate-limiting conditions. Recently, a transcription factor, SLIM1, which is a central transcriptional regulator of plant sulfur response and metabolism, was isolated from Arabidopsis (Maruyama-Nakashita et al., 2006). A series of S-responsive SLIM1-dependent genes were reported, and one of them was found to be UGP3, but not SQD1 or SQD2. Under sulfur-limiting conditions, expression of UGP3 decreases in the wild type, while a decrease in the expression of UGP3 is suppressed in slim1 mutants. These results suggest that the expression of UGP3 and
the other two SQDG biosynthetic genes are coordinately regu-
ulated under normal and phosphate-limiting conditions, but they
are differently regulated when they arestarved for sulfate. These
differences in transcriptional regulation may be derived from a
difference in their evolutionary origins.

METHODS

Chemicals

α-D-[1-13C]Glcuropyanose-1-phosphate (99 atom-% 13C) and α-D-galactopy-
ranose-1-phosphate were purchased from Omicron Biochemicals and
Calbiochem, respectively. UDP-Glc, UTP, and solvents for LC-MS were
taken from Wako Pure Chemical Industries. Other UDP-hexoses,
nucleotide triphosphates, and sulfur monophosphates were purchased
from Sigma-Aldrich. SQDG and glucoside of sitosterol were obtained
from Lrardan Fine Chemicals. Hydrogenated MGDG and hydrogenated
glycerolipid from soybeans were obtained from Avanti Polar Lipids.

Plant Materials

Seeds of the T-DNA insertion line for the ugp3-1, ugp3-2, and sqd1
mutants (SALK_020654, SALK_073806, and SALK_016799, respectively)
were obtained from the ABRC. The T-DNA insertion site was confirmed
by sequencing of PCR fragments. The primers used for this study are listed
in Supplemental Table 1 online. The PCR fragment at the left border of the
T-DNA was amplified using LB1 and gene-specific primers (ugp3-1_Rv
for SALK_020654, ugp3-2_Rv for SALK_073806, and sqd1_Rv for
SALK_016799). Unless stated otherwise, plants were grown on agar-
solidified Murashige and Skoog (MS) medium containing 1% (w/v) glucose
and 3% (w/v) sucrose at 22°C under a 16-h-light/8-h-dark cycle. After an 18-d
incubation, the aerial regions were harvested 6 h after the onset of the light
phase. For lipid analyses of plants grown under phosphate-controlled
conditions, wild type (Columbia-0 accession) plants, ugp3-1, ugp3-2, and
sqd1 mutants were grown on phosphate-controlled medium with suffi-
cient phosphate (10 mM) for 10 d and then transferred to either phosphate-
sufficient (10 mM) or phosphate-depleted (0 mM) medium prepared as
described by HärteI et al. (2000) and grown for another 10 d. For lipid
analyses of plants grown under sulfate-controlled conditions, plants
were grown on MS medium for 10 d and then transferred to either MS medium
or sulfate-depleted (0 mM) MS medium by replacing MgSO4 with MgCl2
for another 2 d. For isolation of intact chloroplasts, plants were grown on
soil at 22°C under a 16-h-light/8-h-dark cycle for 45 d.

Coexpression Analyses

Coexpression analyses were performed using a Coexpression Gene
Search algorithm on the RIKEN PRIME website (Akiyama et al., 2008)
and ATTED-II (Obayashi et al., 2007). The Coexpression Gene Search
program is a web-based application designed to identify corre-
lated genes from gene expression data produced using transcriptome
data. All data sets of version 3 of ATTED II (tissue and development, stress
and hormone treatments) were used for the analyses as
described by Yonekura-Sakakibara et al. (2007). At first, the coexpression
relationship among all genes described below was analyzed by the
Coexpression Gene Search program (matrix, all data sets v:3; method,
intersection of sets; threshold value, +0.5), and highly coexpression
gene clusters were narrowed down. Then, these coexpressing genes
were newly utilized for query for Coexpression Gene Search (matrix, all
data sets v:3; method, intersection of sets; threshold value, +0.5). Genes
that coexpressed with at least two of the query genes were selected, with
considering annotations for function genes. Then, the expression coef-
ficient of these selected genes was analyzed again by Coexpression
Gene Search program, and the result was downloaded as a Pajek file.
Then, coexpressing gene pairs were visualized by connecting with lines
using a network analysis program, Pajek (http://vlado.fmf.uni-lj.si/pub/
networks/pajek/). We applied a layout algorithm (Kamada-Kawai) by
selecting from the layout menu in the Pajek software to adjust the layout
of the nodes. Finally, the layout was adjusted manually. The genes used for
queries in the transcriptome coexpression analysis were as follows:
At4g31780 (MGD1), At5g20410 (MGD2), At2g11810 (MGD3), At3g11670
(DGD1), At4g00550 (DGD2), At4g33030 (SQD1), At5g01220 (SQD2),
At2g01180 (PAP1), At1g15080 (PAP2), At1g62430 (CD51), and
At1g09290 (PGS1).

LC-MS Analysis of Lipid Extracts

Total lipids were extracted according to the method of Bligh and Dyer
(1959). Crude lipid extracts were dissolved in chloroform and subjected to
LC-MS analysis using a Shimadzu LC-MS-IT-TOF mass spectrometer
combined with a Shimadzu LC-20AD HPLC system. A two-solvent
system was used to generate the mobile phase: solvent A, methanol-
water (95:5, v/v) containing 0.2% ammonium formate, pH 5.9; solvent B,
acetoni-trile-methanol-water (95:2.3: v/v/v) containing 0.2% ammonium
formate, pH 5.9. The pH of both solvents A and B was adjusted by adding
30% NH4OH to the mixtures of solvents containing 0.2% (v/v) formic acid.
At the beginning of the gradient, the mobile phase was 100% solvent B for
3.33 min. Solvent B was linearly decreased to 60% over 6.67 min and
successively decreased to 30% over 1.33 min. Solvent B was held at 30% for
3.33 min and then increased to 100% for reequilibration. The flow rate
was held 0.18 mL min −1 for 3.33 min at the beginning of the gradient
and linearly increased to 0.2 mL min −1 over 11.33 min. The flow rate
was then increased to 0.4 mL min −1 at 14.66 min after the beginning of the gradient,
maintained for 13.33 min, and then decreased to 0.18 mL min −1.
Total elution time was 40 min.

High-resolution ESI-MS were acquired in both positive and negative ion
modes by switching the polarity during individual analyses. Conditions for
measurement of ESI-MS were as follows: mass range, m/z 150 to 1600;
interface voltage, 4.5 V; curved desolvation line temperature, 200°C; heat
block temperature, 200°C; ion accumulation time, 10 ms; detector
voltage, 1,800 V; nebulizer gas, N2 (15 L·min−1). The collision-induced
dissociation experiment was performed using Ar as the collision gas, with
a relative collision energy of 50% and a relative collision gas flow of 50%.
Peak areas of individual lipid molecules were calculated based on the
m/z values of their molecular-related ions or fragment ions. The ions used
for calculation of peak areas are as follows: [M+HCOO] + for MGDG and
DGDG, [M-H] − for SQDG and PI, [M+NH3−phosphoglycerol] + for PG,
[M+NH3−phosphoethanolamine] − for PE, and [M+H] + for PC. Because
the lipid species with the same polar head were eluted at almost the
same retention time (see Supplemental Figure 5 online), corrections for
overlap of isotopic variants in higher mass lipids were applied.

Ionization efficiency is largely influenced by the nature of the polar
headgroups. Thus, the ionization efficiency is assumed to be almost
identical when molecules have the same polar headgroups. Levels of
individual lipid molecules in the wild-type plant and mutant lines were
expressed as relative values against the sum of the peak areas of lipid
molecules with the same polar headgroups in the wild type (Figure 3).

Lipid and Fatty Acid Analyses Using Thin Layer Chromatography and
Gas Chromatography–Mass Spectrometry

Lipids from plants grown under phosphate- and sulfate-depleted condi-
tions were extracted and analyzed using thin layer chromatography and
gas chromatography–mass spectrometry. The lipids were separated
using two-dimensional thin layer chromatography followed by fatty acid detection and measurement of membrane lipid content as described by Kobayashi et al. (2007).

### Quantitative Real-Time RT-PCR

Total RNA was isolated using the SV Total RNA Isolation System (Promega) according to the manufacturer’s instructions. Reverse transcription was performed using the PrimeScript RT Reagent Kit (Takara Bio). cDNA amplification was performed using the SYBR Premix Ex Taq (Takara Bio) and 400 nM gene-specific primers. Real-time PCR was performed using the SYBR Green Perfect Real Time Kit (Takara Bio) and the Thermal Cycler Dice Real Time System. mRNA contents were calculated using eIF4A as an internal standard. Three biological replicates were used for quantitative real-time PCR. Gene-specific primers are described in Supplemental Table 1 online.

### Phylogenetic Analysis

Protein sequences were obtained using homologous protein cluster data consisting of protein sequences of *Arabidopsis thaliana* (The Arabidopsis Information Resource [TAIR]; ftp://ftp.Arabidopsis.org/home/tair/Sequences/), *Oryza sativa* (The Rice Annotation Project Database [RAP-DB]; http://rapdb.dna.affrc.go.jp/rapdownload/), *Populus trichocarpa* (Joint Genome Initiative; http://genome.jgi-psf.org/Poptr1_1/Poptr1_1.home.html), *Solana moellendorffii* (Genoscope; http://www.genoscope.cns.fr/externe/Download/Projets/Projet_ML/data/annotation/), *Phytophthora brassicacearum* (see Supplemental Table 1 online). Homologous protein cluster data were constructed using PSI-CD-hit of the CD-HIT program (http://cd-hit.org; Li and Godzik, 2006) with a threshold of identity ≥30% and word size = 2. Other protein sequences were obtained from the National Center for Biotechnology Information database. These sequences were aligned using the ClustalX program (version 2.0.9) (Thompson et al., 1999; Larkin et al., 2007). A phylogenetic tree was constructed using MEGA version 4 (Kumar et al., 1994; Tamura et al., 2007) using the neighbor-joining method (Saitou and Nei, 1987) with Poisson correction, complete deletion, and bootstrap procedures (1000 replicates, random seed).

### Expression and Purification of Recombinant UGP3 Protein

The coding sequence of UGP3 was amplified using PCR with the primers AT3G56040_F0 and AT3G56040_Rnonstop (see Supplemental Table 1 online). The sequence of UGP3-CDS disagreed with that of *At3g56040* deposited in the database of TAIR, and the nucleotide substitutions result in a nonsynonymous change (Asp530Gly). Thus, the corresponding genomic sequence of UGP3 from the Columbia-0 accession was confirmed using genomic PCR with *Replace check_Fw* and *Replace check_Rv* as primers. This study concluded that the 2621st and 2622nd nucleotides of the UGP3 gene are *G* and *A*, respectively (the corresponding nucleotides are *A* and *T* on the TAIR website; see Supplemental Figure 19 and Supplemental Data Set 5 online). Thus, the amino acid at residue 530 in the polypeptide of UGP3 was determined to be Gly. The mature sequence (mUGP3-CDS) that lacks the region encoding chloroplastic transit peptides at N-terminus was amplified by PCR with the primers AT3G56040_F(–72aa) and AT3G56040_Rnonstop (see Supplemental Table 1 online for primer sequences) using UGP3-CDS as template.

The amplified DNA fragment of mUGP3-CDS was subcloned in Nova pET-53-DEST (Merck) using the TOPO directional cloning kit and LR reaction methods (Invitrogen). The plasmid, mUGP3-CDS-pET-53-DEST, was electroporated into the C41(DE3) strain of *Escherichia coli* (Avidis) carrying a chaperon plasmid pG-Ti2 (Takara Bio). The transformed *E. coli* was cultured in Luria broth supplemented with 100 μg mL⁻¹ ampicillin, 20 μg mL⁻¹ chloramphenicol, and 1 ng mL⁻¹ tetracycline at 37°C with shaking until the OD₆₀₀ reached ~0.4. heterologous gene expression was then induced by treatment with 0.35 mM isopropylthio-β-1-galactoside followed by an overnight culture at 25°C. The cells were pelleted by centrifugation (2000g for 5 min) and then resuspended in 50 mM potassium phosphate, pH 7.8, containing 300 mM NaCl, 0.7% (v/v) 2-mercaptoethanol, and 0.5 mM phenylmethylsulfonfyl fluoride (buffer A). The cells were disrupted by sonication, and the soluble protein fraction was recovered by collecting the supernatant after centrifugation at 14,000g for 10 min. The recombinant His-tagged protein was purified using metal chelation chromatography. The soluble protein was applied to a TALON spin column (Takara Bio) equilibrated with buffer A. After washing the column with buffer A supplemented with 10 mM imidazole, proteins were eluted by increasing the concentration of imidazole to 250 mM and subjected to examination for purity and substrate specificity. The concentration of protein was determined by the method of Bradford (1976) with BSA as the standard. The kinetic constants were determined by Hanes-Wolff plot based on the Michaelis-Menten kinetics. The kinetic constant for Glc1P was determined by changing the concentration of Glc1P (0 to 10 mM) in the presence of 10 mM UTP, and that for UTP was determined by changing the concentration of UTP (0 to 10 mM) in the presence of 10 mM Glc1P.

### Assay of UGPase Activity

The standard enzyme assay reaction mixture (final volume, 100 μL) consisted of 50 mM Tris-HCl, pH 7.8, 0.5 mM o-dihexylammonium acetate (Tokyo Chemical Industry); soluble B, methanol containing 5 mM dihexylammonium acetate; gradient, 0 to 3.5 min, 30 to 85% B/A (A = B); flow rate, 0.3 mL min⁻¹; and column temperature, 35°C. Conditions for MS were as follows: scan range, m/z 150 to 700; capillary voltage, 3.0 kV; cone voltage, 30 V; source temperature, 130°C; desolvation temperature, 400°C; cone gas flow, 50 L h⁻¹; desolvation gas flow, 800 L h⁻¹; nebulizer and curtain gas, N₂. For quantification of UDP-Glc, the reaction mixtures were analyzed using selected ion monitoring at m/z 565.05 and 566.06 for [M–H]+ species of unlabeled and labeled UDP-Glc, respectively.

### Transient Expression Assay in Arabidopsis Cells

The YFP fusion N-terminal 200 amino acids of UGP3, including cTPs, were amplified using the primers AT3G56040_F0 and AT3G56040_R(200aa) using UGP3-CDS as template cloned into the ePENT/D-TOPO vector using the pENTR Directional TOPO Cloning Kit (Invitrogen). The entry clone and the Gateway binary vector, pH35GY, were incubated with the LR Clonase Enzyme Mix (Invitrogen) (Kubo et al., 2005). The binary plasmid was transformed to *Arabidopsis* MM1 culture cells using the Agrobacterium tumefaciens method. The cells that transiently expressed cTP-YFP fusion were mounted on glass slides and observed using a confocal laser scanning microscope (LSM510 META,
Isolation of Intact Chloroplasts

The rosette leaves of *Arabidopsis* grown on soil were digested using cell wall–digesting enzymes, and intact protoplasts were isolated according to the method of Robert et al. (2007). Intact protoplasts isolated from rosette leaves of three plants (2 g) were suspended in 5 mL of 50 mM HEPES–HCl buffer, pH 7.5, containing 0.33 M sorbitol, 1 mM MnCl₂, 1 mM MgCl₂, 2 mM EDTA, and 5 mM sodium ascorbate (buffer B). Protoplasts were disrupted by pipetting several times to release chloroplasts. Intact chloroplasts were isolated by centrifugation on a step gradient using Percoll as described by Awai et al. (2001). Intact protoplasts were washed twice with buffer B and suspended in the buffer used for assay of UGPase activity. A portion of the protoplasts was used for measurement of ADH activity, and the residual portion was used for measurement of chlorophyll content as described by Lichtenthaler (1987). ADH activity was determined as described by Dumez et al. (2006).

Analysis of UDP-Glc in *Arabidopsis* Leaves

Rosette leaves of *Arabidopsis* (250 mg fresh weight) grown in soil were frozen in liquid nitrogen and homogenized to a fine powder using a mortar and pestle. The powder was extracted with 2.5 mL of 50% (v/v) methanol for 30 min at 30°C to disrupt the cell membranes and release the cytoplasmic content. The extracts were centrifuged at 3000g for 5 min at 4°C.

Analysis of Gene Duplication

Segmental duplication regions of the genes encoding UGPases in the *Arabidopsis*, rice, poplar, and vine grape genomes were searched for in the PGDD (http://chibba.agtec.uga.edu/duplication/). Segmental duplication regions corresponding to each UGP3 homolog in the genomes were retrieved from the duplicated block data downloaded from PGDD with a threshold score ≥ 300.

Accession Numbers

*Arabidopsis* sequence data from this article can be found in the *Arabidopsis* Genome Initiative database under accession numbers At3g03250, At5g17310, and At3g56040. Other sequence data from this article can be found in the GenBank/EMBL data libraries under accession numbers AAV31019, CAL56361, XP_007323, ABD59006, BAD56763, XP_001980316, CAL56540, Q16222, CAL55944, XP_001982246, ABQ98820, AAF62555, ABD57308, and P19595. As described in Methods, errors were found in the DNA sequence of UGP3 deposited in the *Arabidopsis* Genome Initiative database. The corrected sequences of UGP3 are available in Supplemental Data Set 5 online. Other accession numbers of *Arabidopsis* genes in this article used for transcriptome analysis are as follows: At4g31780 (MGD1), At5g20410 (MGD2), At2g11810 (MGD3), At3g11670 (DGD1), At4g00550 (DGD2), At4g33030 (SQD1), At5g01220 (SQD2), At2g01180 (PAP1), At1g15080 (PAP2), At1g62430 (CDST), and At2g39290 (PGS1).

Supplemental Data

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

**Supplemental Figure 1.** Tissue-Specific Gene Expression Patterns of the SQDG Biosynthetic Genes in *Arabidopsis*.

**Supplemental Figure 2.** Induction of Expression of the SQDG Biosynthetic Genes in Wild-Type *Arabidopsis* under Phosphate Limitation.

**Supplemental Figure 3.** Molecular Organization of UGP3 Mutant Alleles and the Impact of Insertional Mutations on Transcript Expression.

**Supplemental Figure 4.** Identification of SQDG in *Arabidopsis* Leaf Lipid Extract Using Ion Trap Time-of-Flight Mass Spectrometry.

**Supplemental Figure 5.** LC-MS Analyses of SQDG in the Wild Type and ugp3 Mutants.

**Supplemental Figure 6.** Hierarchical Clustering Analysis of Lipid Molecular Species in Wild-Type Plants and ugp3 Mutants.

**Supplemental Figure 7.** LC-MS Analysis of Methanolic Extracts from the Leaves of Wild-Type Plants and ugp3 Mutants.

**Supplemental Figure 8.** Sequence Alignment of *Arabidopsis* UGP3 and Homologs.

**Supplemental Figure 9.** Purification of UGP3 expressed in *E. coli*.

**Supplemental Figure 10.** Mass Spectra of Standard UDP-Glc and the Reaction Product by Recombinant UGP3.

**Supplemental Figure 11.** Micrographs Showing Chloroplast Targeting of UGP3.

**Supplemental Figure 12.** Decrease in UGPase Activity in Chloroplasts in *ugp3* Mutants.

**Supplemental Figure 13.** Quantification of the Transcript Level of UGP3 in the Wild Type under Phosphate- and Sulfate-Depleted Conditions.

**Supplemental Figure 14.** Syntenic Relationships among the UGP3 Homologs in Plants.

**Supplemental Figure 15.** Putative UGP3 Homolog in *Physcomitrella patens*.

**Supplemental Figure 16.** Evolutional Studies of the UGP3 Homologs in Plants.

**Supplemental Figure 17.** Evolutional Studies of Type A UGPase Homologs in Higher Plants.

**Supplemental Figure 18.** Changes in Expression Levels of SQD1, SQD2, and UGP3 under Sulfur Starvation Conditions.

**Supplemental Figure 19.** Partial Genomic Sequence of UGP3.

**Supplemental Table 1.** Primers Used in This Study.

**Supplemental Data Set 1.** Text File of Alignment Corresponding to Figure 4.
Supplemental Data Set 2. Text File of Alignment Corresponding to Figure 8 and Supplemental Figure 16.

Supplemental Data Set 3. Text File of Alignment Corresponding to Supplemental Figure 8.

Supplemental Data Set 4. Text File of Alignment Corresponding to Supplemental Figure 17.

Supplemental Data Set 5. Partial Genomic Sequence of Arabidopsis UGP3 (At3g56040) and Corrected Sequences of Corresponding Genome, cDNA, and Amino Acids.

Supplemental References.

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A Chloroplastic UDP-Glucose Pyrophosphorylase from *Arabidopsis* Is the Committed Enzyme for the First Step of Sulfolipid Biosynthesis

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