An Arabidopsis Callose Synthase, GSL5, Is Required for Wound and Papillary Callose Formation

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Arabidopsis was transformed with double-stranded RNA interference (dsRNAi) constructs designed to silence three putative callose synthase genes: GLUCAN SYNTHASE-LIKE5 (GSL5), GSL6, and GSL11. Both wound callose and papillary callose were absent in lines transformed with GSL5 dsRNAi and in a corresponding sequence-indexed GSL5 T-DNA insertion line but were unaffected in GSL6 and GSL11 dsRNAi lines. These data provide strong genetic evidence that the GSL genes of higher plants encode proteins that are essential for callose formation. Deposition of callosic plugs, or papillae, at sites of fungal penetration is a widely recognized early response of host plants to microbial attack and has been implicated in impeding entry of the fungus. Depletion of callose from papillae in gsl5 plants marginally enhanced the penetration of the grass powdery mildew fungus Blumeria graminis on the nonhost Arabidopsis. Paradoxically, the absence of callose in papillae or haustorial complexes correlated with the effective growth cessation of several normally virulent powdery mildew species and of Peronospora parasitica.

INTRODUCTION

Callose is a (1→3)-β-D-glucan that is widely distributed in higher plants and is readily recognizable in tissue sections through the formation of an intense yellow, UV light-induced fluorescence with the aniline blue fluorochrome (Stone et al., 1985). During normal plant growth and development, callose is found as a transitory component of the cell plate in dividing cells, as is a major component of pollen mother cell walls and pollen tubes, and is found as a structural component of plasmodesmatal canals. Callose also has been observed in abscission zones and on sieve plates in dormant phloem (Stone and Clarke, 1992).

In addition to its role in normal growth and development, callose is deposited between the plasma membrane and the cell wall after exposure of plants to a range of abiotic and biotic stresses, including wounding, desiccation, metal toxicity, and microbial attack (Stone and Clarke, 1992). Particular attention has been focused on callose formation in plant–microbe interactions, during which plant host cells respond to microbial attack by rapidly synthesizing and depositing callose as plugs, drops, or plates in close proximity to the invading pathogen (Ryals et al., 1996; Donofrio and Delaney, 2001). These callosic deposits are commonly referred to as papillae and are thought to contain, in addition to (1→3)-β-D-glucan, minor amounts of other polysaccharides, phenolic compounds, reactive oxygen intermediates, and proteins (Smart et al., 1986; Bolwell, 1993; Bestwick et al., 1997; Thordal-Christensen et al., 1997; Heath, 2002). Although the precise function of callosic papillae during microbial attack has not been demonstrated unequivocally, it has been postulated that the papillae act as a physical barrier to impede microbial penetration (reviewed by Stone and Clarke, 1992). By slowing or immobilizing the invading microorganisms, the host plant could focus upon them a number of antimicrobial compounds, such as wall-degrading enzymes, phytoalexins, and active oxygen species, or initiate cascade responses involving race-specific resistance genes (Brown et al., 1998).

The central importance of callose deposition in several key plant processes, both under normal growth conditions and after abiotic or biotic stress, has prompted many attempts to purify and characterize callose synthases from plants. To date, no highly purified callose synthase preparations have been reported; therefore, it has not been possible to demonstrate a direct link between callose synthase activity and amino acid or nucleotide sequence. Nevertheless, evidence is accumulating that callose synthases are encoded by a family of glucan synthase–like (GSL) genes (Cui et al., 2001; Doblin et al., 2001; Hong et al., 2001a; Østergaard et al., 2002), based on the homology of these plant genes with yeast FKS06 hypersensitivity (FKS) genes, which also are believed to be involved in (1→3)-β-D-glucan biosynthesis (Douglas et al., 1994; Cabib et al., 2001; Dijkgraaf et al., 2002).
Twelve GSL genes have been identified in Arabidopsis (Richmond and Somerville, 2000; Verma and Hong, 2001; http://cellwall.stanford.edu/), in which individual members of the family presumably mediate the synthesis of callose in different tissues and/or under different environmental conditions. Very limited information is available about the biological functions of individual AtGSL family members. GSL6 (CalS1) is located at the growing cell plate and interacts with two cell plate–associated proteins, phragmoplastin and a UDP-glucose transferase (Hong et al., 2001a, 2001b). The three proteins likely form part of a larger complex that assembles at the cell plate (Hong et al., 2001b). Transgenic tobacco lines overexpressing a GREEN FLUORESCENT PROTEIN (GFP)-AtGSL6 construct showed increased callose deposition at the cell plate, but this gene failed to complement the yeast mutant fks1 (Hong et al., 2001a). AtGSL5 has been shown to partially complement fks1 and is inducible by salicylic acid (Østergaard et al., 2002). Despite these observations, direct genetic evidence linking GSL genes to callose biosynthesis in plants generally, or genetic evidence linking individual AtGSL family members to specific sites of callose deposition in Arabidopsis, has yet to be found.

The work described here was initiated in an attempt to identify members of the Arabidopsis GSL gene family that might be upregulated after wounding and when Arabidopsis leaves are exposed to the powdery mildew fungus Blumeria graminis. This ascomycete is a common fungal pathogen of grasses but fails to produce disease in nonhost interactions with Arabidopsis or other dicot plants (Braun et al., 2002). Semiquantitative reverse transcriptase–mediated PCR indicated that, of the 12 Arabidopsis GSL genes, transcript levels for GSL5, GSL6, and GSL11 increased slightly after inoculation of leaves with B. graminis spores; on this basis, these genes were chosen for further examination (our unpublished data). Here, we assign the GSL5 isoform (referred to as CalS12 by Hong et al. [2001a]) a crucial role in inducible callose accumulation upon wounding and during biotic stress. Contrary to the common belief that callose accumulation contributes to plant defenses against pathogen attack, our data indicate that callose synthesized by the wound-responsive GSL5 might protect the fungus during pathogenesis.

RESULTS

GSL Transcript Levels Are Reduced in Double-Stranded RNA Interference Lines

Fertile transgenic T3 Arabidopsis lines were obtained for each of the three double-stranded RNA interference (dsRNAi) constructs, which targeted GSL5, GSL6, and GSL11. The GSL5, GSL6, GSL11, and empty vector control lines exhibited no obvious morphological abnormalities. DNA gel blot hybridization analyses confirmed the presence of the dsRNAi construct in each line, most of which carried single copies of the transgene (data not shown). When total RNA was extracted from young leaves and inflorescences of dsRNAi lines for quantitative real-time PCR analysis, mRNA for the three GSL genes was generally 3- to 10-fold less abundant than in the empty vector controls and wild-type lines (Figure 1).
grains in the three dsRNAi transgenic lines were examined with the aniline blue fluorochrome, callosic deposits in the GSL5 line appeared normal (data not shown). No differences were observed in any of the GSL dsRNAi lines for cell plate or plasmodesmata callose (data not shown).

Given that fungal penetration is likely to cause wounding of plant cells, the formation of callosic plugs was examined in transgenic GSL dsRNAi lines after inoculating leaves with spores from the virulent powdery mildew fungus *Sphaerotheca fusca*. Elongating fungal hyphae were observed in all cases, and the rate of hyphal growth on the leaf surface did not differ substantially between the lines for at least 48 h after inoculation. Callosic papillae that stained brightly with the aniline blue fluorochrome were clearly evident in all independent GSL6, GSL11, and control lines (Figure 3). By contrast, in all independent GSL5 transgenic lines, callosic plugs were completely absent, despite the fact that hyphal growth occurred (Figure 3).

**Wound and Papillary Callose Also Are Reduced in a GSL5 T-DNA Insertion Line**

To confirm that the effects in the GSL5 dsRNAi lines were specific to the lack of the GSL5 callose synthase isoform, we examined a T-DNA insertion line (GABI-KAT 089H05) containing an insertion in the second exon of GSL5. When leaves of homozygous T-DNA insertion siblings (referred to as *gsl5-1*) were wounded or inoculated with *S. fusca*, they showed similar, dramatic reductions in wound callose and papillary callose formation (data not shown).

Inoculation with conidiospores of the *B. graminis* powdery mildew failed to produce disease on wild-type Arabidopsis leaves. Microscopic examination revealed normal conidiospore germination, with production of primary and differentiated appressorial germ tubes in contact with the leaf surface. However, the germ tubes typically failed to enter the nonhost epidermal cells (92% of interaction sites) and were accompanied by the formation of callosic papillae (Figures 4A to 4C). This infection phenotype is similar to other reported nonhost interactions between plants and fungal pathogens (Kobayashi et al., 1997; Heath, 2002). By contrast, callosic plugs were virtually undetectable in both the homozygous GSL5 T-DNA insertion line (*gsl5-1*) and the GSL5 dsRNAi lines (Figures 4B and 4C). *B. graminis* penetration indices were only slightly higher in *gsl5-1* than in wild-type plants (Figure 4A), suggesting that callose plays a minor role in resistance to wall penetration. In T2 progeny obtained after selfing of the GABI-KAT 089H05 T1 line, which was hemizygous for the T-DNA insertion, siblings homozygous or hemizygous for the T-DNA insertion in GSL5 co-segregated with the absence or presence of callosic plugs, respectively, beneath *B. graminis* appressoria (Figure 5). Despite the absence of callosic plugs in *gsl5-1* mutant plants, round papillae still were clearly recognizable beneath fungal appressoria (Figure 4C), indicating that components other than callose were present in these subcellular structures.

A cell death response was observed in epidermal cells that were penetrated by *B. graminis* sporelings at ~48 h after spore inoculation (~15% of interaction sites; Figure 4A). In contrast to epidermal cells that were not penetrated by the fungus, com-

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**Figure 2. Reduced Callose Accumulation at Wound Sites in GSL5 dsRNAi Lines.**

Leaves of wild-type (WT) plants and GSL5, GSL6, and GSL11 dsRNAi lines were wounded by cutting with a razor. Aniline blue fluorochrome staining of leaves revealed reduced callose accumulation at wound sites after 24 h. Bars = 200 μm.
Complete collapse and browning of cytoplasm was observed in epidermal cells containing haustoria in wild-type and gsl5-1 genotypes. Cytoplasmic collapse and browning is considered a reliable indicator of cell death (Heath, 1998). Trypan blue staining was used to confirm these observations (data not shown). Cell death was accompanied by an intense aniline blue fluorochrome staining pattern along the entire cell margin in wild-type plants, whereas dead epidermal cells in gsl5-1 mutants showed only a punctate callose staining pattern at the cell periphery (Figure 4D). The punctate staining pattern in gsl5-1 plants was reminiscent of plasmodesmata that are known to contain callose (Northcote et al., 1989; Itaya et al., 1998); therefore, we conclude that the absence of heavy GSL5 callose deposition at cell margins in gsl5-1 plants reveals the underlying plasmodes-
Wild-type (WT) and T-DNA insertion (gsl5-1) plants were inoculated with *B. graminis* f. sp. *hordei* conidiospores.

(A) Quantitative analysis of *B. graminis* penetration rate. At least 300 interaction sites between *B. graminis* sporelings and leaf epidermal cells were scored for the presence or absence of fungal haustoria at the times indicated.

(B) Callose depositions at sites of attempted *B. graminis* cell wall penetration (arrowheads) are visible by fluorescence microscopy on wild-type but not *gsl5-1* plants 24 h after inoculation. Bars = 200 μm.

(C) Higher magnification views of papillae (arrowheads) beneath fungal appressoria in wild-type (top row) and *gsl5-1* (bottom row) plants. Light microscopy images are shown at left, and corresponding fluorescence images after aniline blue fluorochrome staining are shown at right. Bars = 10 μm.

(D) Invasive growth of *B. graminis* (successful haustorium differentiation) in single epidermal cells of wild-type leaves leads to cell death and callose deposition along the entire cell margin. Fluorescence images were taken 48 h after inoculation, and leaves were stained with the aniline blue fluorochrome. Note the relatively low-intensity punctate fluorochrome staining pattern at the cell periphery in *gsl5-1* plants. agt, appressorial germ tube; ha, haustorium; ps, punctate staining; sp, conidiospore; st, stomata. Bars = 50 μm.
mata callose. This finding indicates that massive GSL5 callose accumulation normally occurs along the cell margin during pathogen-triggered cellular suicide and that the GSL5 cell margin callose and the plasmodesmata callose are synthesized by different callose synthase isoforms of the same cell.

The Mutant *powdery mildew resistant4-1* Contains a Defective GSL5 Gene

The Arabidopsis mutant *powdery mildew resistant4-1* (*pmr4-1*) was shown previously to be resistant against *Erysiphe cichoracearum* and to lack callose at fungal penetration sites; the recessive mutation was mapped to the long arm of chromosome 4 (Vogel and Somerville, 2000). We noticed that GSL5 is located in the same chromosomal region and tested whether *pmr4-1* might contain a mutation in GSL5. Direct DNA sequencing revealed a single base substitution (G→A) in genomic DNA of *pmr4-1* corresponding to position 2060 in the deduced coding sequence, whereas the sequence derived from wild-type plants was identical to the GSL5 gene in the databases. The base substitution would result in the conversion of the TGG codon for Trp-687 in the protein into a TAG stop codon. The gray triangle represents the T-DNA insertion site in the GABI-KAT 089H05 line (*gsl5-1*). The dotted line above exon 3 shows the target sequence used to generate the GSL5 dsRNAi construct.

**Figure 5.** Lack of Callose Deposition Cosegregates with T-DNA Insertion in GSL5.

Absence of aniline blue fluorochrome staining after inoculation with *B. graminis* correlates with a homozygous T-DNA insertion (ins.) in GSL5. Segregating progeny (18 T2 siblings) of a selfed hemizygous T-DNA GSL5 insertion line were genotyped molecularly and tested for callose deposition upon challenge with *B. graminis*. Gel electrophoretic separation of PCR products obtained with a GSL5– and T-DNA–specific oligonucleotide primer indicated the presence of the T-DNA insertion in all individuals except sibling 10 (bottom gel). The absence of a PCR amplification product using oligonucleotide primers designed to bind on either side of the T-DNA insertion site in GSL5 exon 2 demonstrated that siblings 2, 5, 6, 9, and 11 are homozygous for the T-DNA insertion (top gel).

**Figure 6.** Scheme of GSL5 Gene Structure and Deduced GSL5 Protein Topology.

(A) GSL5 gene structure. Black boxes represent exons, and lines indicate introns. The asterisk indicates the mutation site in *pmr4-1* that generates a stop codon. The gray triangle represents the T-DNA insertion site in the GABI-KAT 089H05 line (*gsl5-1*). The dotted line above exon 3 shows the target sequence used to generate the GSL5 dsRNAi construct.

(B) GSL5 is predicted to be a polytopic integral membrane protein with ~14 transmembrane helices. Both the NH2 and COOH termini are predicted to be orientated toward the cytoplasm, as is the putative catalytic domain, which is located in an extended loop between predicted transmembrane helices 6 and 7. Mutation sites in *pmr4-1* and *gsl5-1* are indicated as described in (A). PM, plasma membrane.

GSL5 and PMR4 Are the Same Gene

Mutant *pmr4-1* plants were reported previously to exhibit resistance against *E. cichoracearum* and the oomycete *Peronospora parasitica* (Vogel and Somerville, 2000). We challenged *pmr4-1*, *gsl5-1*, and the GSL5 dsRNAi lines with another virulent powdery mildew species, *Golovinomyces orontii*. In contrast to susceptible wild-type Arabidopsis, comparable enhanced disease resistance was observed (Figure 7A), indicating that the absence of PMR4 or GSL5 confers similar broad-spectrum resistance. When *pmr4-1* plants were inoculated with *B. graminis* spores, the infection phenotype was indistinguishable from that observed in the *AtGSL5* dsRNAi and *gsl5-1* plants, and callosic papillae were not detected (see above). To determine whether *PMR4* and GSL5 might be the same gene, we crossed the homozygous T-DNA insertion line (*gsl5-1*) with the *pmr4-1* mutant. Inspection of 15 F1 plants after fungal spore inoculation with the virulent *G. orontii* powdery mildew showed enhanced disease resistance and lack of callose accumulation at attempted infection sites. The observed infection phenotypes of the F1 plants were indistinguishable from the *pmr4-1* and *gsl5-1* parental lines (data not shown), strongly indicating that *PMR4* and GSL5 are the same gene.

**GSL5 Is Required for Callose Encasement of Haustorial Complexes**

We examined the enhanced disease resistance phenotype to *G. orontii* (Figure 7A) in greater detail at the microscopic level (Figures 7B to 7D). This revealed indistinguishable hyphal growth on wild-type and *gsl5-1* leaves at 72 h after spore inoculation.
Figure 7. GSL5-Dependent Infection Phenotypes upon Challenge with the Powdery Mildew Fungus G. orontii.

Wild-type (WT) and T-DNA insertion (gsl5-1) plants were inoculated with G. orontii conidiospores.

(A) Single detached leaves from plants 10 days after inoculation. The surface of the leaf from the wild-type plant is covered by macroscopically visible hyphae, whereas mutants pmr4-1 and gsl5-1 develop no visible disease symptoms.

(B) Hyphal growth on the leaf surface at the commencement of callose encasement of haustorial complexes in wild-type and gsl5-1 plants at 72 h after inoculation. A bright-field image is shown at left, and the corresponding fluorescence image after callose staining is shown at right. gsl5-1 plants lack an intense aniline blue fluorochrome staining indicative of callose deposition at haustorial complexes. sh, secondary hyphae. Bars = 200 μm.

(C) A dense fungal mycelium and numerous conidiophores (cp) with long conidial chains as well as numerous local callosic deposits are visible on wild-type plants. A bright-field image is shown at left, and the corresponding fluorescence image after callose staining is shown at right. gsl5-1 plants show significantly reduced conidiophore formation and shorter conidial chains. Bars = 200 μm.

(D) Higher magnification images of mature haustorial complexes encased by GSL5 callose from wild-type and gsl5-1 plants. A bright-field image is shown at left, and the corresponding fluorescence microscopic image after callose staining is shown at right. Bars = 10 μm.
(Figure 7B, bright field). However, reduced hyphal growth and severely diminished conidiophore formation became detectable on gsl5-1 leaves at 5 and 10 days after pathogen challenge (Figure 7C, bright field). This finding indicates that pathogen growth on the mutant plants is impaired significantly but is not inhibited completely. A striking encapsulation of haustorial complexes with callose was found in wild-type but not in gsl5-1 leaves, suggesting that GSL5 participates in callose synthesis both in papillae and at haustoria before and after fungal entry into epidermal cells (Figure 7D). This encasement of haustorial complexes was recognizable as early as 72 h after spore inoculation (Figures 7B and 7C, epifluorescence). This finding corroborates our earlier observations of dynamic changes of GSL5 activity or location as the infection process progresses and might indicate a critical role for callose in the function of haustorial complexes.

DISCUSSION

To define potential roles of GSL genes in callose biosynthesis in plants, dsRNAi constructs that specifically target 3 of the 12 putative GSL genes in Arabidopsis—GSL5, GSL6, and GSL11—were used to generate stable transformants. Quantitative PCR showed that transcript levels of the three genes were reduced specifically in the dsRNAi transgenic lines. No evidence for compensatory upregulation of other GSL genes was detected. For example, in the GSL5 lines, GSL6 and GSL11 mRNA remained at approximately the same levels as observed in the control and wild-type plants (data not shown). During the initial design of the dsRNAi constructs, regions in which sequences of 21 nucleotides were identical in any two different AtGSL genes were avoided (Hamilton and Baulcombe, 1999), but quantitative PCR showed some downregulation of AtGSL genes most closely related to the target genes (AtGSL1, AtGSL3, and AtGSL7, respectively; data not shown). Therefore, it was clear that the dsRNAi results would require independent confirmation through T-DNA insertion lines or other mutants in which a single gene had been disrupted. Although mRNA abundance for the specific GSL genes was lower in each of the corresponding dsRNAi transgenic lines, it was not abolished completely (Figure 1), presumably because dsRNAi silencing occurs post-transcriptionally (Fire et al., 1998) or because of potential cell type–specific differences in the activity of the 35S promoter, which drove the expression of the dsRNAi constructs (Sunilkumar et al., 2002).

In seeking a link between GSL expression and callose deposition, it was noticed initially that wound callose was reduced greatly, specifically in the GSL5 dsRNAi plants (Figure 2). Wounding is an inherent consequence of fungal penetration of plant cells, so the effects of fungal challenge on the dsRNAi lines were examined. When the transgenic plants were challenged with several fungal species, the response of the dsRNAi GSL5 lines differed markedly from that of the dsRNAi GSL6, dsRNAi GSL11, and control plants. In particular, papillary callose was absent in the dsRNAi GSL5 line after inoculation of leaves with the fungal pathogens S. fuscum, G. orontii, and B. graminis. Similar results were observed with the T-DNA insertion line GABI-KAT 089H05, in which the GSL5 callose synthase gene is disrupted (Figure 6). As mentioned above, our focus was shifted from the dsRNAi lines to the homozygous GABI-KAT 089H05 T-DNA insertion line (gsl5-1). Although papillary callose was not detectable in gsl5 plants, the typical round wall appositions that form beneath fungal appressoria, at least at the light microscopic level, were indistinguishable from those in wild-type plants except that they contained no callose (Figure 4C). Therefore, it seems unlikely that callose serves as an essential structural scaffold in papillae (cf. Smart et al., 1986; Bolwell, 1993). The formation of noncallosic papillae in gsl5 plants indicates that the accumulation of papillary components other than callose continues.

The phenotypic characteristics of the gsl5 lines were similar to those described for the powdery mildew–resistant pmr4-1 mutant of Arabidopsis (Vogel and Somerville, 2000). We have shown here that the pmr4-1 line has an internal stop codon in GSL5 that is located in a similar position to the T-DNA insertion in the GABI-KAT 089H05 line in exon 2 of the gene (Figure 6). Based on a number of topology prediction programs, the lesions will disrupt the protein sequence close to the last transmembrane helix before the large, nonmembrane, and presumably cytoplasmic region of the protein that is widely assumed to contain the catalytic site (Figure 6) (Cui et al., 2001; Doblin et al., 2001; Hong et al., 2001a; Østergaard et al., 2002). It is highly unlikely that the truncated protein would have any callose synthase activity. Thus, our gene-silencing experiments and the mutant data clearly demonstrate a role for AtGSL5 in the deposition of wound and papillary callose. More generally, the data provide strong genetic evidence that the products of GSL genes are essential for callose formation in higher plants.

It has long been believed that callosic papillae physically impede pathogen entry into plant cells, although this is not accepted universally (reviewed by Stone and Clarke, 1992). To test this hypothesis, we took advantage of a nonhost interaction phenotype between Arabidopsis and the grass powdery mildew fungus B. graminis, which is characterized by the failure of the pathogen to penetrate leaf epidermal cells on wild-type plants at most interaction sites (Figure 4A). Penetration incidence was only slightly higher in gsl5 mutants, and infection did not occur. In other work, Arabidopsis mutants have been identified in which B. graminis penetration through the cell wall was increased dramatically, but none of these showed reduced callose formation at papillae (V. Lipka and P. Schulze-Lefert, unpublished data). Together, these observations indicate that resistance to wall penetration by the grass powdery mildew fungus is a plant–controlled process to which papillary callose does not contribute to any great extent. However, nonhost interactions with other fungal pathogens need to be tested on gsl5 plants before we can generalize our observations with the B. graminis pathogen.

A striking finding in the present work was the different spatial and temporal accumulation patterns of GSL5 callose at different subcellular sites in single cells, namely at papillae and haustorial complexes, as well as along the entire cellular periphery after pathogen-provoked cell death (Figures 4 and 7). These changing patterns might reflect local stimulation of the activity of preexisting callose synthase enzyme or the specific targeting of newly synthesized enzyme to cellular “stress sites.”
Each of the three pathogen-triggered GSL5 callose accumulation patterns is consistent with a plasma membrane location for the callose synthase, given that the extrahaustorial membrane is thought to be continuous with the plasma membrane (Giese et al., 1997; Mendgen and Hahn, 2002). At this stage, we favor the existence of a mechanism that mediates tight subcellular control of the activity of preexisting enzymes. The activity of plasma membrane-bound plant callose synthases often is dependent on Ca2+, whereas in yeast, the Rho1 GTPase regulates the activity of the callose synthase homologs FKS1 and FKS2 by altering their phosphorylation status (Qadota et al., 1996; Calonge et al., 2003). A rapid increase in cytoplasmic free Ca2+ levels is a common response of plant cells to pathogen challenge (Blume et al., 2000; Grant et al., 2000) and wounding (Leon et al., 1998, 2001); therefore, it is conceivable that local increases in Ca2+ concentrations beneath fungal appressoria and at haustorial complexes contribute to local GSL5 stimulation (Leon et al., 1997; Mendgen and Hahn, 2002). At this stage, we favor the activity of the callose synthase homologs FKS1 and FKS2 dependent on Ca2+ plasma membrane–bound plant callose synthases often is decreased (Giese et al., 2003). A rapid increase in cytoplasmic free Ca2+ levels after more widespread plasma membrane disintegration as the cell dies might contribute to GSL5 activation along the entire cell periphery.

Perhaps the most surprising observation with the gsl5 lines is their enhanced resistance to attack by different biotrophic pathogens (Figure 7A). It was shown previously that the loss of PMR4 function does not result in the constitutive expression of salicylic acid– or ethylene– and jasmonic acid–dependent defense pathways (Vogel and Somerville, 2000). Although Ostergaard et al. (2002) showed salicylic acid–dependent GSL5 gene expression, we have shown a link between GSL5 activity and wounding (Figure 2). Wounding of the cell wall is a feature of pathogenesis by biotrophic microorganisms that must enter plant cells for nutrient supply. Biotrophic pathogens such as P. parasitica and E. cichoracearum might have exploited components of the wound response for successful pathogenesis. It is conceivable that callose might be needed as a physical support for fungal development, either as a structural scaffold to accommodate haustorial complexes or to allow optimal nutrient uptake via this specialized feeding structure. Because cell wall penetration resistance was not altered substantially in the absence of callosic plugs and because haustorium differentiation was not impaired in any detectable manner upon challenge with the tested virulent pathogens in gsl5 leaves (Figure 7D), a structural role of GSL5 callose for “intracellular” accommodation of fungal infection structures seems unlikely.

However, GSL5 callose might either facilitate nutrient uptake by haustoria or serve as a pathogen-induced protection barrier that prevents the recognition of pathogen-derived molecules by the host. For example, lack of callose might unmask fungal wall polysaccharides and/or secreted proteins. Certain branched (1→3,1→6)-β-D-oligoglucosides and chitin/chitosan oligosaccharides released from these fungal wall polysaccharides (Bartnicki-Garcia, 1968) by partial endohydrolysis are highly active elicitors of plant defense responses, even at concentrations as low as 10 nM (Côté and Hahn, 1994). By contrast, linear (1→3)-β-D-oligoglucosides of the type that would be released from callose itself by the (1→3)-β-D-glucanases are not active in eliciting plant defense (Côté and Hahn, 1994). The evolution of (1→3)-β-D-glucanase inhibitors by pathogenic fungi implies that inhibiting the release of (1→3,1→6)-β-D-oligoglucosides could be important for the establishment of fungal infection (Rose et al., 2002).

METHODS

Plant Lines and Growth Conditions

The Arabidopsis thaliana GSL5 T-DNA insertion line GABI-KAT 089H05 was provided by Bernd Weisshaar (Max-Planck-Institute for Plant Breeding Research) and had been generated in the GABI-Kat program (http://www.mpiz-koeln.mpg.de/GABI-Kat/GABI-Kat_homepage.html). Oligonucleotide sequences used for T-DNA insertion detection were 5’-CGCAGATGCTGATTTAAGCTCAAGATAAATGTTAAATATT-3’ and 5’-CATGATAGTTAGTTAGGAAATACATCAATGATTT-3’ (GSL5 specific and T-DNA left border specific, respectively). The powdery mildew-resistant line pmmr-1 was obtained from John Vogel and Shauna Somerville (Carnegie Institution of Washington, Stanford, CA). Plants were transformed by the floral-dip method (Clough and Bent, 1998) using Agrobacterium tumefaciens strain GV3101::pmPmpR[K] with the binary vectors pAJS, pAJ6, and pAJ7. T3 plants used in infection experiments were grown in a glasshouse at 22°C. Seedlings (10 days old) transformed with double-stranded RNA interference (dsRNAi) constructs were selected by spraying every second day for 1 week with 100 mg/L Basta (AgraEvo, Düsseldorf, Germany).

dsRNAi Constructs

Gene-specific inverted repeats separated by an intron were inserted into plasmid pJawohl3 (AF404854) to create pAJ5 (GSL5; At1g05570), pAJ6 (GSL11; At1g59110), and pAJ7 (GSL5At4g03550) dsRNAi constructs. Primer combinations used to produce the gene-specific sense and antisense GSL dsRNAi fragments were as follows: for AtGSL5, 5’-CATGATAGTTAGTTAGGAAATACATCAATGATTT-3’ and 5’-GGAAGGGCGCGGAGATTTGATG-3’; for AtGSL11, 5’-CATGATAGTTAGTTAGGAAATACATCAATGATTT-3’ and 5’-GGGTTTGCTGTTTCAACTGTAGT-3’ (230-bp product); for AtGSL6, 5’-CATCGATAAAGGATCCCATACCGTCT-3’/5’-GGGTTTGCTGTTTCAACTGTAGT-3’ (230-bp product); for AtGSL5At4g03550, 5’-CATCGATGAAAGGATCCCATACCGTCT-3’/5’-CATCGATGAAAGGATCCCATACCGTCT-3’ (230-bp product); and for AtGSL6, 5’-GGAAGGGCGCGGAGATTTGATG-3’/5’-GGGTTTGCTGTTTCAACTGTAGT-3’ (230-bp product).

DNA and RNA Extractions

Genomic DNA was extracted from young leaves of Arabidopsis using the hot cetyl-trimethyl-ammonium bromide method (Lassner et al., 1989). Total RNA was extracted from young leaves and inflorescences of dsRNA lines using the Trizol reagent (Invitrogen, Carlsbad, CA) according to the manufacturer’s instructions.

Quantitative PCR Analysis of GSL mRNA

Total RNA (5 μg) was used in cDNA reactions using the Superscript II cDNA synthesis kit (Invitrogen). The cDNA was diluted 2.5-fold, and 1 μL was taken for quantitative real-time PCR in 20-μL reaction volumes using 10 μL of 2× Quanti-Tect PCR master mix (Qiagen, Valencia, CA). 0.3 μM gene-specific primers, and 0.6 μL of a 100-fold dilution of SYBR Green I dye (Applied Biosystems, Foster City, CA). PCR cycling and fluorescence measurements were performed with a Rotorgene 2000 Real-Time Cycler RG2072 (Corbett, Sydney, Australia), and data were normalized against glyceraldehyde phosphate dehydrogenase (GAPDH), actin (Actin1), and cyclophilin (Cyclo) mRNA levels (Vandecampe et al., 2000).
The formation of callosic plugs was examined in 4- to 6-week-old plants 48 h after inoculating leaves with spores from the powdery mildew fungus *Sphaerotheca fusca*. Four- to 6-week-old Arabidopsis plants were inoculated with spores of *S. fusca* and *Blumeria graminis* and sampled 48 h later. The presence of callosic plugs was determined using a combination of histological and histochemical assays. The plugs were visualized using light microscopy and stained with the callose-specific fluorochrome 4,6-diamidino-2-phenylindole (DAPI) to detect DNA accumulation.

**Pathogenicity Assays**

Wounding

Four- to 6-week-old plants were wounded by cutting leaves with a razor. After 24 h, the leaves were detached, cleared, and stained for callose accumulation.

**Microscopic Analyses**

Tissue fixation and staining of fungal structures and callose were performed as described previously (Peterhänsel et al., 1997; Vogel and Somerville, 2000). Tissues were examined with a Zeiss Axiosplan 2 fluorescence microscope (Carl Zeiss, Oberkochen, Germany). Epi-illumination was used at an excitation cutoff limit of 365 nm with barrier filter KP520.

Upon request, materials integral to the findings presented in this publication will be made available in a timely manner to all investigators on similar terms for noncommercial research purposes. To obtain materials, please contact Paul Schulze-Lefert, schleif@mpiz-koeln.mpg.de.

**ACKNOWLEDGMENTS**

We thank John Vogel and Shauna Somerville for providing the *pmr4-1* line, Nell Shirley for assistance with the quantitative PCR experiments, and Bruce Stone for helpful suggestions. This work was supported by grants from the Grains Research and Development Corporation and the Australian Research Council (to G.B.F.) and from the Max Planck Society (to P.S.-L.).

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Dijkgraaf, G.J., Abe, M., Ohya, Y., and Bussey, H. (2002). Mutations in Fks1p affect the cell wall content of β-1,3- and β-1,6-glucan in *Saccharomyces cerevisiae*. Yeast 19, 671–690.


2002). Primers used in the quantitative PCR were as follows: for AtGAPDH (At3g26650), 5′-TGTTGAGCTGTCTGAGGTCTC-3′/5′-GAGCGGCAATGGCAGTATC-3′; for AtActin1 (At2g37620), 5′-TGGCAGC-AATGGAACTGGAAGT/3′/5′-GATAGCATGGAAAGTCATAC-3′; for AtCyc (At2g36130), 5′-TGGCAGAAGCTGGCTACTTAC-3′/5′-AACACTGGCCTCGC-GCATT-3′; for AtGSL5 (At4g03550), 5′-CTGGAATCCTGAGCTCTGTG/3′/5′-TGGCCTTATTAGTTCTCCTCAGT-3′; for AtGSL6 (At1g05570), 5′-GAAGGTTGGGCGTCGGAAAG/5′-CAA-TGGAAGCATTCCCCCACCAG-3′; and for AtGSL11 (At3g59100), 5′-TTATAGGTTGGAGGACTCGTGAA/5′-TTGTCTTTCCGACCA-GCGAATCA-3′.

**Sequence Analysis of PMR4-1**

The three exons of GSL5 (1870, 2022, and 1448 bp, respectively) were amplified by PCR using flanking oligonucleotide primers. Purified PCR products (NucleoSpin extraction kit; Macherey-Nagel, Düren, Germany) were subjected to direct DNA sequencing. DNA sequences were determined by the MPIZ DNA core facility on Applied Biosystems (Weiterstadt, Germany) ABI Prism 377 and 3700 sequencers using BigDye-terminator chemistry. Forward/reverse primers used for GSL5 exon amplification and sequencing from *pmr4-1* and *gsl5-1* plants were as follows: Exon1, 5′-ATTGTTTTCCTGGAATGCT-3′/5′-TCAAGTGCAAA-GCCTTGTAC-3′; Exon2, 5′-CGACGATGCTGCAATAA-3′/5′-CAGTATAGTATTGAAATATACCC-3′; and Exon3, 5′-GATTATTACCTAATGACTGATCAGTATGACTGAC/3′. Additional sequencing primers were as follows: Exon1b-F, 5′-GATAATGCTGGAGGACTACCGA-3′; Exon1b-R, 5′-AGCCAGAGATTCGCGGCACC-3′; and Exon2b-F, 5′-GAT-TCTCACCCTAGGGAC-3′.

**Wounding**

Four- to 6-week-old plants were wounded by cutting leaves with a razor. After 24 h, the leaves were detached, cleared, and stained for callose accumulation.

**Pathogenicity Assays**

The formation of callosic plugs was examined in 4- to 6-week-old plants 48 h after inoculating leaves with spores from the powdery mildew fungus *Sphaerotheca fusca*. Four- to 6-week-old Arabidopsis plants were inoculated with spores of *Golovinomyces orontii* and *Blumeria graminis* as described previously (Peterhänsel et al., 1997; Vogel and Somerville, 2000).

**Microscopic Analyses**

Tissue fixation and staining of fungal structures and callose were performed as described previously (Peterhänsel et al., 1997; Vogel and Somerville, 2000). Tissues were examined with a Zeiss Axiosplan 2 fluorescence microscope (Carl Zeiss, Oberkochen, Germany). Epi-illumination was used at an excitation cutoff limit of 365 nm with barrier filter KP520.

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NOTE ADDED IN PROOF

During the processing of this manuscript, Nishimura et al. (Nishimura, M.T., Stein, M., Hou, B.H., Vogel, J.P., Edwards, H., and Somerville, S.C. [2003]. Loss of a callose synthase results in salicylic acid-dependent disease resistance. Science 301, 969–972) published work on Arabidopsis pmr4 mutants. They showed that PMR4 encodes GSL5 callose synthase and demonstrated that resistance to powdery mildew infection is mediated through the salicylic acid pathway.
An Arabidopsis Callose Synthase, GSL5, Is Required for Wound and Papillary Callose Formation
Andrew K. Jacobs, Volker Lipka, Rachel A. Burton, Ralph Panstruga, Nicolai Strizhov, Paul Schulze-Lefert and Geoffrey B. Fincher

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