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Signaling role of oligogalacturonides derived during cell wall degradation

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In addition to the role of the cell wall as a physical barrier against pathogens, some of its constituents, such as pectin-derived oligogalacturonides (OGAs) are essential components to trigger signaling pathways that induce rapid defense responses. Many pathogens directly penetrate the cell wall to access water and nutrients of the plant protoplast, and a rigid cell wall can fend off pathogen attack by forming an impenetrable physical barrier. Thus, cell wall integrity sensing is one mechanism by which plants may detect pathogen attack. Moreover, when the plant-pathogen interaction occurred, OGAs released during cell wall modification can trigger plant defense (e.g., production of reactive oxygen species, production of anti-microbial metabolites and synthesis of pathogenesis-related proteins). This review documents and discusses studies suggesting that OGAs play a dual signaling role during pathogen attack by inducing defense responses and plant architecture adjustment.

The capacity of plants to survive adverse conditions and reach reproductive maturity critically depends on their ability to continuously adapt to changes in the environment. In particular, a plant attacked by a pathogen can resist infection by activating its own defense strategies in a timely manner.

For definition, an optimal immune system for long-lived organisms requires high specificity, self-tolerance and immune memory. The immune system in animal is the most studied and most sophisticated. By comparison, the immune system of plants seems to be far less complex. Because plants lack an adaptive immune system, it immune system is called "innate immune system." The innate immune system is an ancient, robust and broad-spectrum defense system that protects plants against invading microbes.[1,2]

Plant Cell Wall Elicitors

The plant cell wall is a complex extracellular structure that plays an important roles in plant growth and development.[3] The plant cell wall is composed for a complex network of polysaccharides, cellulose, hemicellulose and pectin.[4] The main load-bearing component of the wall is cellulose that is composed by fibers of 30–36 chains of β-1,4-linked glucose. These fibers are interconnected with hemicellulose polymer (xyloglucan or arabinoxylan) and both polymers are embedded in the matrix of pectin [a mixture of complex polysaccharides, of which the main component is polygalacturonic acid, a homopolymer of (1→4)-α-D-galacturonic acid (GalA) units].[5]

All plant pathogens interact with plant cell wall as initial obstacle. Plant cell wall provides a physical barrier and also highly dynamic structure that is remodeled after pathogen attack.[6] Pathogens by mechanical force and/or producing enzymes capable of degrading the plant cell wall, directly penetrate the cell wall to access water and cellular nutrients.[7,8] After pathogen attack, plants deposit callose (glucan polymers) rich cell wall appositions at sites of attempted pathogen penetration, accumulate phenolic compounds and synthesize lignin polymers to reinforce the wall[9] following the activation of host defense pathways. The first active line of defense occurs at the plant cell surface when pathogens-associated molecular patterns (PAMPs), such as structural components of the pathogen cell wall (chitin, glucan) and bacterial flagellins, are detected by pattern-recognition receptors (PRRs).[10]

Moreover, during plant-pathogen interaction, plant cell wall breakdown fragments have been shown to elicit various defense responses. For instance, degradation of cellulose by β-1,4-glucanases generates cellodextrin and degradation of the homogalacturonic domain of pectin generates [1→4]-α-linked oligologalacturonides (OGAs).[6,11-13] This defense response include reinforce the protection provided by plant cell wall, generation and accumulation of reactive oxygen species (ROS), production of antimicrobial compounds such as phytoalexins and synthesis of pathogenesis-related proteins (PR).[2]

OGAs are the best-characterized plant cell wall derived elicitors. However, not all OGAs are capable of eliciting a defense response. Their ability to elicit a response depends on length [degree of polymerization (dp) higher than 9],[13-17] degree of methyl esterification[18-21] and level of acetylation.[22]

Treatment of plants with exogenous OGAs showed to initiate the production of ROS and the accumulation of transcripts such as phenylalanine ammonia-lyase gene (*PAL*), which is the first enzyme in the phenylpropanoid pathway leading to phytoalexins and lignin production[6,23] as well as changes in gene expression in the salicylic acid (SA), ethylene (ET) and jasmonic acid (JA) pathways.[18,24,25] In grapevine, treatment with OGAs showed to accumulate hydrogen peroxide (H_2O_2) and an increase in *PAL* and various PR genes.[14,24] In Arabidopsis, OGAs induced the expression of several defense genes, including *PAD3*, which encodes the

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cytochrome P450 (CYP71B15) enzyme that catalyzes the last step in camalexin biosynthesis.[16] In wild strawberry, external addition of OGAs produced an accumulation of SA as well as an increase expression of a pathogenesis-related gene, *PR5*.[18]

Signaling Through Cell Wall Damage

Recently, analyses of several mutants highlighted the importance of cell wall modification in the plant–pathogen interaction. The pmr6 mutant, with a mutation in a pectate lyase-like gene,[26] and the pmr5 mutant, with a mutation in a gene of unknown function,[27] exhibited resistance to some powdery mildew species. Both mutants exhibited a strong increase in total uronic acid content, suggesting that PMR5 and PMR6 affect pectin composition. The penetration success of the power mildew pathogen on these two mutants resembles wild type suggesting that a change in cell wall digestibility by this pathogen was not responsible for the disease resistance phenotype. Therefore, it is possible that the changed cell wall or altered pectin fragments released during fungal attack stimulate plant defenses in both mutants.[28] Other study in fruits of the wild strawberry overexpressing *FaPE1*, a fruit-specific pectin methyl esterase gene (*PME)* from the cultivated strawberry showed a pectin modification.[18] These transgenic fruits inoculated with spores of *Botrytis cinerea* were more resistant to the growth this pathogen. Moreover, it was demonstrated that this was due to the presence of partially de-methylated OGAs in the transgenic fruits, which had constitutively activated the salicylic acid signaling pathway. It is achievable that these de-methylated OGAs were released because the pectin was modified.

The Arabidopsis mutant cev1, identified by its enhanced resistance to powdery mildew, is mutated in CESA3, which encodes a cellulose synthase, and its resistance was attributed to constitutive activation of the jasmonate-signaling pathway, presumably due to a decrease in the amount of cellulose.[29,30] Additionally, mur3 mutants, which are affected in a xyloglucan galactosyltransferase, showed an increase in the levels of SA in their petioles and were resistant to *Hyaloperonospora parasitica*.[31]

How is the cell damage detected by the plants? Nowadays, it is not fully understood. The cell damage maybe sensed by the detection of damage to polysaccharides, inhibition of cell wall synthesis or assembly, release of OGAs and other degraded cell wall fragments. Recently, the Arabidopsis wall-associated kinase1 (WAK1) has been described as a receptors of OGAs.[32] Also a receptor-like kinase (RLK) has been identified that mediate responses to cellulose deficiency which suggests the CrRLK1L protein family as a new candidate for cell wall integrity sensors.[33]

Involvement of Auxin in Plant Responses to OGAs

It is very well known that signaling for defense is interconnected with hormones pathways. ET, JA and SA pathways are clearly components of signal transduction to resistance, however, other hormones such as auxin have more complex network with defense signaling.[34]

Besides inducing defense responses, OGAs can also affect several aspects of plant growth and development. In particular, a number of studies have been reported to have an antagonistic role to auxin. From our knowledge, the first evidence of this antagonistic role between auxin and OGAs was shown in pea stem segments in which auxin-induced growth was competitively inhibited by elicitor-active OGAs.[35] Therefore, the capacity of OGAs to antagonize auxin may play an important role during development. Indeed, OGAs were shown regulate several developmental related processes such as root growth and alteration in lateral root formation,[36,37] adventitious root formation[38,39] and pericycle cell differentiation.[40] Furthermore, in tobacco, OGAs inhibited the induction of the late auxin-responsive genes *Nt114*, *rolB* and *rolD*.[41] In cucumber seedling, OGAs treatment allowed more rapid recovery of root growth in auxin-treated roots.[42] The role of OGAs in wild strawberry development was revealed by larger size of ripe fruits.[43] It would be important to know whether or not OGAs and auxin act independently or of there is an interaction between their signaling pathways. To date, the mechanism underlying the antagonistic effect of OGAs and auxin-induced responses has not been described yet.

Conclusions

Plant cell walls are highly complex in structure and in composition. Why are they so complex? In 1978, it was suggested that some of the structural complexity could represent latent signal molecules involved in defense rather that structures required for the mechanical function of the wall.[44] Nowadays, it is known that the induction of defense pathways by plant cell wall damage supports the role of cell wall not only a physical barrier between pathogens and the internal contents of plant cells but also as an important sensor for downstream signaling pathways. Some progresses have been made with recent analyses of plant mutants and transgenics of plant responses to cell wall damage. However, much remains to be discovered about identification of more plant cell wall derived elicitors as well as its receptors and how the plant cell wall signals is traduced to induce the defense responses and others changes in plant growth and development.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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