Modulating host homeostasis as a strategy in the plant-pathogen arms race

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In plant-pathogen interactions, pathogens aim to overcome host defense responses while plants employ a battery of responses to limit pathogen growth and thus disease. In this “arms race” between hosts and pathogens, horizontal gene transfer is a potent source of pathogenic innovation for viruses and bacteria. However, bacteria rarely acquire eukaryotic-like genes from their hosts, and where they appear to, evidence for a role of the acquired genes remains outstanding. We have recently reported experimental evidence that the citrus canker causing pathogen Xanthomonas axonopodis pv. citri contains a plant natriuretic peptide-like gene (XacPNP) that encodes a protein that modulates host homeostasis to its advantage. We argue that Xanthomonas PNP has been acquired in an ancient horizontal gene transfer, and that plant and bacterial PNPs trigger a number of similar physiological responses, we make a case of molecular mimicry. Released XacPNP mimics host PNP and results in a suppressed host response, “improved” host tissue health and consequently better pathogen survival in the lesions. Finally, we propose that Xanthomonas axonopodis pv. citri host interactions can serve as model system to study the role of host homeostasis in plant defense against biotrophic pathogens.

The molecular basis of bacterial pathogenesis has been studied extensively and significant progress has been made in recent years, including the elucidation of several mechanisms used by animal and plant pathogens operating during colonization of host tissue. Particularly in plant-pathogen interactions, a key concern has been the function of bacterial effector proteins delivered into the host cell by the type III protein secretion system. These effector proteins are able to modulate the plant basal defense response for the benefit of the pathogen. In turn, plants employ a battery of responses to limit pathogen growth and thus disease, such as the production of signaling molecules and reactive oxygen species, cell wall thickening and increased defense gene expression.1,2 Another strategy used by plants in this arms race is the starvation of the pathogen through the modification of its carbohydrate metabolism.3 Under such conditions of resource limitation pathogen survival would greatly benefit by overcoming homeostatic host defense strategies.

Plant natriuretic peptides (PNPs) are molecules with a role in the systemic regulation of ion and water homeostasis.4 PNPs act via rapid and transient increases in cellular cGMP levels5 and promote tissue specific ion movements,6 increases in net water uptake into cells as well as stomatal opening.7,9 PNPs are upregulated under conditions of osmotic stress10 and K+ starvation11 and have been localized in conductive tissue.12 Furthermore, PNP has been identified in the apoplastic proteome13 and biologically active PNP was isolated from xylem exudates.12 A number of directly and/or indirectly PNP-dependent cellular processes are presented in a model (Fig. 1) and these findings, together with the PNP localization studies point to a complex role of PNPs in the systemic regulation of plant homeostasis and growth.

Surprisingly, Xanthomonas axonopodis pv. citri, the bacteria responsible for citrus canker, but no other phytopathogen or bacteria has a PNP-like gene (XacPNP). This suggested a specific role of this gene in the struggle of the pathogen for colonization of citrus plants. In a recent report, we have expressed and purified XacPNP and demonstrated that the bacterial protein alters physiological responses including stomatal opening in plants and improves photosynthesis parameters. We also determined that XacPNP expression was specifically and strongly induced in planta. Moreover, when XacPNP deletion mutants were infiltrated in host plants, lesions became more necrotic than those observed in the wild-type.14 Our results showed that XacPNP is able to induce and/or maintain photosynthesis in infected tissues during colonization and hence generate a supply of assimilates. XacPNP also caused starch degradation in guard cells resulting in an increase in solute content which in turn causes stomatal opening as well as an influx of water to the infected area, and hence a well hydrated microenvironment for the pathogen. In
summary, XacPNP is modulating host homeostasis through mimicry with a plant-like molecule to “improve” the host status to suit its biotrophic lifestyle.

Horizontal gene transfer events are well established between prokaryotic species and from prokaryotic sources to eukaryotic recipients. On the other hand, horizontal gene transfer from eukaryotes to prokaryotes appears to be rare and the examples reported include genes encoding proteins involved in metabolic pathways leading to better adjustment to environmental conditions. Fructose bisphosphate aldolase, shikimate pathway enzymes and glyceraldehydes 3-phosphate dehydrogenase are some of the examples. More remarkable are the few cases described for gene transfer between host and pathogens in which the acquired mechanism plays a critically important role since it allows recipients to adapt to new ecological niches. An outstanding recent study revealed that Legionella pneumophila, the causative agent of Legionnaires’ disease, contains 44 uncharacterized genes with many distinct eukaryotic motifs and different G + C content lending support to the hypothesis that they were acquired through horizontal gene transfer and may serve to modulate host cell functions to the pathogen’s advantage.

Bacterial plant pathogens have evolved through an arms race where new attack strategies led to the evolution of better defense mechanisms, as reflected in the successive developments in virulence and disease resistance mechanisms. Considering that X. axonopodis pv. citri is not free-living, we propose that XacPNP was acquired by the bacteria and evolved in the pathogen to contribute to the optimal adaptation of this strain to the specific host environment.

While the origin of the XacPNP is difficult to ascertain with any degree of certainty, we have argues for an ancient lateral gene transfer that must have occurred before the monocot/dicot split, mainly because XacPNP does not cluster with either. An ancient lateral gene transfer would suggest that we might in time discover a PNP in a more primitive plant that is the true ancestor of XacPNP and in addition, we may also expect to find other bacteria, evolved from the original recipient of the plant gene that also contain PNP.

Finally, Xanthomonas axonopodis pv. citri and its host interactions have turned out to be a most useful system to study the role, importance and mechanisms of changes in plant homeostasis in the defense against biotrophic bacterial pathogens. The next major challenges will be to characterize XacPNP signaling in host cells as well as the systematic action of this peptide in the whole plants.

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