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## **Generic signal-specific responses: cytokinin and context-dependent cellular responses**

Muller, B

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## DARWIN REVIEW

# Generic signal-specific responses: cytokinin and context-dependent cellular responses

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## Abstract

The phytohormone cytokinin triggers numerous and diverse responses during the plant life cycle via a two-component phosphorelay signalling system. Each step of the signalling cascade is supported by a gene family comprising several members. While functional redundancy is observed among family members, additional gene-specific functions encoded by *cis*-regulatory and coding sequence of individual family members have been described and contribute to specificity in signalling output. In addition, the cellular context of the signal-receiving cell affects the response triggered. Recent studies in *Arabidopsis* have demonstrated how expression of cytokinin signalling components predefines a spatiotemporal map of signalling sensitivity, which causes local signal amplification and attenuation. In summary, the specific interpretation of cytokinin signalling is affected by an orchestrated interplay of signalling genes and cellular context.

**Key words:** *Arabidopsis thaliana*, cytokinin signalling, development, pattern formation, plant hormones, signalling specificity.

## Introduction

Plants and animals represent parallel realizations of multi-cellular development and display vastly different life cycles. They have independently evolved genes for pattern formation and cell–cell communication (Meyerowitz, 2002). In spite of the differences, common developmental strategies exist. For example, in contrast to the countless and diverse instances of cell-to-cell signalling, a surprisingly small repertoire of signal transduction systems is used. Research of the past two decades has revealed that the deployment of each transduction pathway is very flexible, and that a handful of core pathways are repeatedly implemented throughout metazoan development to account for innumerable cases of cell specification events (Davidson and Erwin, 2006). Similarly, in plants, signalling cascades triggered by phytohormones are used throughout the life cycle to affect cellular identities and responses (Santner *et al.*, 2009). Given the contrast between the few signalling systems and the innumerable cellular responses they trigger, the general question arises as to how fairly ubiquitous and generic signals can elicit specific and context-dependent cellular responses? Generally, specificity is achieved by regulating

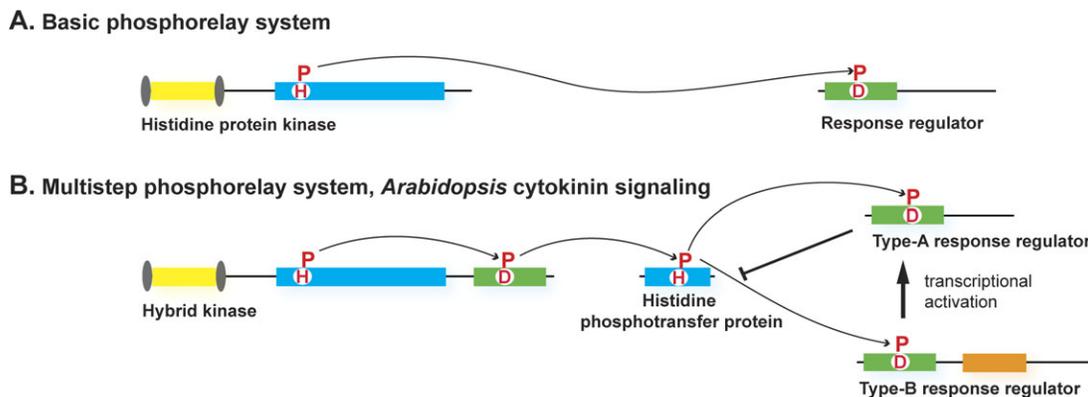
the localization, quantity, and quality of the signalling activity, and the status of the receiving cell. In this review, specificity and regulation of intracellular signalling will be discussed with regard to the cytokinin signalling circuitry; for discussions about how the availability and localization of active ligands is regulated, the interested reader is referred to recent reviews (Werner and Schmülling, 2009; Kudo *et al.*, 2010).

Cytokinins comprise a class of adenine-derived signalling molecules. The first cytokinin, Kinetin, was isolated as a breakdown product from autoclaved herring-sperm DNA, based on its cell-division promoting activity in cultivated tobacco tissue (Miller *et al.*, 1955; Amasino, 2005). Later, a number of additional effects provoked by cytokinins were described: stimulated leaf expansion and seed germination (Miller, 1956, 1958), delayed senescence in leaves (Richmond and Lang, 1957; Gan and Amasino, 1995), *de novo* organ formation from cultured tissue (Skoog and Miller, 1957), or release from apical dominance (Wickson and Thimann, 1958; Cline *et al.*, 1997), and more (Mizuno, 2005; To and Kieber, 2008; Jeon *et al.*, 2010; Perilli *et al.*, 2010).

## Cytokinins are perceived by a multistep phosphorelay system

The identification of the *CYTOKININ INDEPENDENT ONE (CKI1)* gene from *Arabidopsis thaliana* (Kakimoto, 1996) was the long-awaited breakthrough, which initiated the molecular elucidation of the cytokinin signal transduction pathway in the following years. Its overexpression caused the typical cytokinin responses in tissue culture (Kakimoto, 1996) and *in planta* (Hwang and Sheen, 2001). *CKI1* encodes for a hybrid kinase, suggesting it functions in a phosphorelay system. Phosphorelay, or two-component signalling systems, are prevalent in bacteria (West and Stock, 2001). In the simplest form, they consist of two conserved proteins: a histidine protein kinase and a response regulator protein that are phosphorylated at conserved His and Asp residues, respectively. Phosphotransfer from the histidine kinase to the response regulator results in activation of the latter (Fig. 1A). More complex versions of this two-component phosphotransfer involve multiple phosphotransfer steps, and often more than two proteins (Fig. 1B). Further evidence supporting the use of a phosphorelay system for cytokinin signalling came when additional genes with conserved His- and Asp-containing domains were identified, such as response regulators (RR), and histidine phosphotransfer proteins (HPT) (Mok and Mok, 2001). A forward genetic screen using tissue culture assays led to the identification of the *cytokinin response 1-1 (cre1-1)* mutation, allelic to the previously characterized *woodenleg (wol)* mutation (Mähönen *et al.*, 2000; Inoue *et al.*, 2001). The same gene was independently isolated and named as *ARABIDOPSIS HISTIDINE KINASE 4 (AHK4)* (Ueguchi *et al.*, 2001). The *CRE1/WOL/AHK4* gene encodes for a true cytokinin receptor that, unlike *CKI1*, could bind and respond to cytokinins (Suzuki *et al.*, 2001; Yamada *et al.*, 2001). The completion of the

*Arabidopsis* genome sequence allowed researchers systematically to compile the potential signalling components, based on the characteristic signatures of domains implicated in phosphorelay signalling (Fig. 2; Hwang *et al.*, 2002). Functional reconstitution of the pathway in an *Arabidopsis* cellular system established the core logic of the pathway (Fig. 1B, Hwang and Sheen, 2001). Pathway activation is initiated by autophosphorylation at a conserved His residue of the receptors, which is subsequently carried-over to a conserved Asp of the receiver domain. The phosphoryl group is then transferred to the functional *Arabidopsis* histidine phosphotransfer proteins (AHP) proteins (Imamura *et al.*, 1999; Suzuki *et al.*, 2000). AHP proteins can form dimers and shuttle between nucleus and cytosol in a cytokinin-independent manner (Punwani *et al.*, 2010). From the AHPs, the phosphate gets passed-over to the nuclear-localized response regulators. Type-B *Arabidopsis* response regulators (type-B ARR) act as transcriptional activators, while type-A *Arabidopsis* response regulators (type-A ARR) negatively interfere with pathway activity, most likely by competing with type-B ARRs for access to the AHPs, and by acting as phosphate sinks (To *et al.*, 2007). Transcription of type-A ARR is directly induced by the activated B-type ARRs (D'Agostino *et al.*, 2000), which establishes a negative feedback loop to the pathway (Hwang and Sheen, 2001). Structurally and functionally, the type-C ARRs resemble type-A ARRs, as they contain a conserved receiver domain and their ectopic expression represses cytokinin output strongly. However, unlike type-A ARRs, their expression does not depend on cytokinin. No aberrant phenotypes have been observed with loss-of function mutants under normal growth conditions, however, since *ARR22* expression was found to be induced by wounding, their functions may become relevant upon conditions of mechanical stress (Kiba *et al.*, 2004; Gattolin *et al.*, 2006; Horák *et al.*, 2008).



**Fig. 1.** Schematic representation of the two-component and the multistep phosphorelay signalling systems. (A) The basic phosphorelay system uses a single phosphoryl transfer event between a His protein kinase and its cognate response regulator. (B) The multistep His-to-Asp phosphorelay system, in which a His-containing phosphotransfer protein (HPT) serves as a phosphoryl acceptor and donor between the hybrid protein kinase (HK) and the response regulators (RR). The activation of the type-B RRs results in transcriptional activation. Type-A RRs attenuate signalling activity. Transcriptional activation of repressive type-A RRs establishes a negative feedback loop to the pathway.

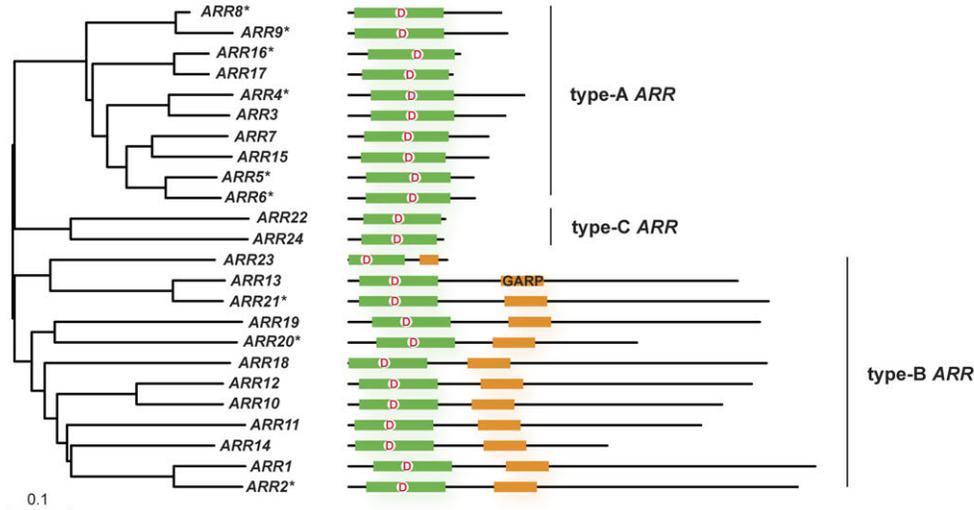
## Hybrid Kinases (HK) implicated in cytokinin signaling



## Arabidopsis Histidine Phosphotransfer proteins (AHP)



## Arabidopsis Response Regulators (ARR)



**Fig. 2.** Compilation of cytokinin signalling components from *Arabidopsis*, and their phylogenetic relationship. On the left, the phylogenetic relationship of *Arabidopsis* family members is shown for the HKs with a well-defined role in cytokinin signalling, for the AHPs, and the ARRs. Alignments were created using the MAFFT-E-INS-i algorithm (Kato and Toh, 2008), based on full-length protein sequences retrieved from TAIR (Swarbreck *et al.*, 2008). Unrooted Neighbor-Joining trees (Saitou and Nei, 1987) were calculated using a BLOSUM62 matrix. The scale bar represents 0.1 amino acid substitutions per site. On the right, the proteins are indicated as black lines. Conserved domains are indicated as boxes. The cytokinin-binding CHASE domains are drawn as yellow boxes, transmembrane segments as grey ovals. Receptor-like domains (RLD) as a grey box. Kinase/transmitter (in HKs) and transmitter domains (in AHPs) with the conserved His residue that gets phosphorylated are depicted as blue boxes; receiver domains, with the conserved Asp residue (D), are indicated by a green box. The DNA-binding GARP domain of the type-B ARRs is indicated by an orange box. The GARP domain of ARR23 is truncated. Asterisks denote genes products with a documented specific function within cytokinin signalling, as discussed in the text.

### Functional studies reveal redundant and gene-specific functions of family members

For each step in the signalling cascade, multiple genes are encoded in the *Arabidopsis* genome (Fig. 2; Table 1). The question arises as to which degree the expansion of each gene family reflects functional diversification? On the one hand, functional studies *in planta* and in heterologous systems supported the core function of different family members in the signalling circuitry; on the other hand, gene-specific functions emerged as well. Sequence comparisons within protein families reveal stretches of poor conservation (Fig. 2). For example, beyond their conserved domains, both type-A and type-B ARRs harbour stretches of sequences that exhibit little similarity within the protein family. Such variable parts can be expected to mediate gene-

specific functions. Furthermore, the analysis of the transcription profiles of cytokinin signalling components *in planta* uncovered complex patterns (Ferreira and Kieber, 2005), which reflects diversity in expression. Thus, gene-specific functions appear to depend both on protein sequence and expression patterns.

In general, loss-of-function mutations in single genes resulted in only subtle phenotypes, revealing the functional redundancy within gene families (Table 1). An exception is the hybrid kinase *CKII*; its loss caused female gametophyte lethality (Pischke *et al.*, 2002; Hejatko *et al.*, 2003; Deng *et al.*, 2010). To obtain stronger phenotypes, plants were generated that harbour loss-of-function mutations in several to all genes belonging to a family, comprising the true receptors (Higuchi *et al.*, 2004; Nishimura *et al.*, 2004;

**Table 1.** List of mutants affecting cytokinin signalling genes, including higher-order mutants

Gene abbreviation	Mutants	Molecular characterization	Phenotypes	References
<b>Hybrid kinases</b>				
<i>CKI1</i>	<i>cki1-1,1-2,1-3,1-4</i>	Gain-of-of function, T-DNA activation tagging mutants, insertions in promoter of <i>CKI1</i>	Ectopic cytokinin activities, resulting in absence of roots and normal flowers, and sterility	Kakimoto, 1996
	<i>cki1-6</i>	Loss-of-function, T-DNA insertion in exon 3	Female gametophyte lethality	Pischke <i>et al.</i> , 2002
	<i>ckil-1</i>	Loss-of-function, En-1 transposon insertion in exon 6	Female gametophyte lethality	Hejatko <i>et al.</i> , 2003
	<i>CKI1(RNAi) 5-3</i>	RNA-interference transgene, causing reduction of endogenous <i>CKI1</i> mRNA levels	Vascular defects	Hejatko <i>et al.</i> , 2009
	<i>cki1-8</i>	Loss- and gain-of function, estradiol-inducible activation tagging T-DNA insertion in promoter of <i>CKI1</i>	Ectopic cytokinin activities upon estradiol applications, female gametophyte lethality without estradiol	Deng <i>et al.</i> , 2010
<i>AHK4</i>	<i>wol</i>	Recessive, dose-dependent dominant negative allele, missense mutation T278I	Determinate root growth phenotype, resulting from a reduced number of cell divisions in the procambium and abnormal differentiation of all vascular cells into protoxylem	Mahonen <i>et al.</i> , 2006b, 2000
	<i>cre1-1</i>	Loss-of function, missense mutation G437D	None under normal conditions, reduced cytokinin-dependent shoot formation in tissue culture, cytokinin-insensitive root growth	Inoue <i>et al.</i> , 2001
	<i>cre1-2</i>	Loss-of function, T-DNA insertion in exon 2	Increased primary root length	Inoue <i>et al.</i> , 2001; Riefler <i>et al.</i> , 2006
	<i>ahk4-1</i>	Hypomorphic, T-DNA insertion in intron 9	None under normal conditions, cytokinin-insensitive root growth	Nishimura <i>et al.</i> , 2004
	<i>cre1-12</i>	Loss-of-function, T-DNA insertion in intron 2	None under normal conditions, reduced relative WUS transcript levels in SAM upon ectopic cytokinin application	Higuchi <i>et al.</i> , 2004; Gordon <i>et al.</i> , 2009
<i>AHK3</i>	<i>ahk3-1</i>	Loss-of-function, T-DNA insertion in exon 9	None under normal conditions	Nishimura <i>et al.</i> , 2004
	<i>ahk3-3</i>	Hypomorphic, T-DNA insertion in intron 6	Increased root meristem cell number and root growth	Higuchi <i>et al.</i> , 2004; Dello Iorio <i>et al.</i> , 2007
	<i>ahk3-7</i>	Loss-of-function, T-DNA insertion in intron 1	Reduced rosette diameter, reduced chlorophyll content, increased root meristem cell number and root growth	Riefler <i>et al.</i> , 2006; Dello Iorio <i>et al.</i> , 2007
	<i>ore12-1</i>	Gain-of-function, missense mutation P243S	Delayed leaf senescence	Kim <i>et al.</i> , 2006
<i>AHK2</i>	<i>ahk2-1</i>	Loss-of-function, T-DNA insertion in exon 7	None under normal conditions	Nishimura <i>et al.</i> , 2004

Table 1. Continued

Gene abbreviation	Mutants	Molecular characterization	Phenotypes	References
AHK2, AHK3	<i>ahk2-2</i>	Loss-of-function, T-DNA insertion in exon 5	None under normal conditions, reduced relative WUS transcript levels in SAM upon ectopic cytokinin application	Higuchi <i>et al.</i> , 2004; Gordon <i>et al.</i> , 2009
	<i>ahk2-5</i>	Loss-of-function, T-DNA insertion in exon 4	None under normal conditions	Riefler <i>et al.</i> , 2006
	<i>ahk2-1 ahk3-1</i>		Semi-dwarf phenotype in aerial part	Nishimura <i>et al.</i> , 2004
	<i>ahk2-2 ahk3-3</i>		Smaller leaves, shorter stems than wild type	Higuchi <i>et al.</i> , 2004
AHK2, AHK4	<i>ahk2-5 ahk3-7</i>		Markedly reduced rosette size, reduced final height, strongly reduced chlorophyll content, strongly enhanced root branching and primary root growth	Riefler <i>et al.</i> , 2006
	<i>ahk2-1 ahk4-1</i>		None under normal conditions	Nishimura <i>et al.</i> , 2004
	<i>ahk2-2 cre1-12</i>		None under normal conditions	Higuchi <i>et al.</i> , 2004
	<i>ahk2-5 cre1-2</i>		Increased lateral root formation	Riefler <i>et al.</i> , 2006
AHK3, AHK4	<i>ahk3-1 ahk4-1</i>		None under normal conditions	Nishimura <i>et al.</i> , 2004
	<i>ahk3-3 cre1-12</i>		None under normal conditions	Higuchi <i>et al.</i> , 2004
	<i>ahk3-7 cre1-2</i>		Increased lateral root formation	Riefler <i>et al.</i> , 2006
AHK2, AHK3, AHK4	<i>ahk2-1 ahk3-1 ahk4-1</i>		Strongly reduced size due to fewer and smaller cells, sterile, strongly reduced SAM	Nishimura <i>et al.</i> , 2004
	<i>ahk2-2 ahk3-3 cre1-12</i>		Very slow root and shoot growth, decreased leaf number, sterile, strongly reduced SAM	Higuchi <i>et al.</i> , 2004
	<i>ahk2-5 ahk3-7 cre1-2</i>		Miniature plants, strongly reduced fertility, retarded flowering, strongly reduced chlorophyll content, increased seed size (maternal/endosperm effect),	Riefler <i>et al.</i> , 2006
<b>Histidine phosphotransfer proteins</b>				
AHP1	<i>ahp1</i>	Loss-of-function, T-DNA insertion in intron 1	None	Hutchison <i>et al.</i> , 2006
AHP2	<i>ahp2-1</i>	Hypomorphic, T-DNA insertion in intron 3	None	Hutchison <i>et al.</i> , 2006
	<i>ahp2-2</i>	Loss-of-function, T-DNA insertion in exon 4	None	Deng <i>et al.</i> , 2010
AHP3	<i>ahp3</i>	Loss-of-function, T-DNA insertion in exon 1	None	Hutchison <i>et al.</i> , 2006
AHP4	<i>ahp4</i>	Hypomorphic, T-DNA insertion in intron 4	None	Hutchison <i>et al.</i> , 2006
AHP5	<i>ahp5-1</i>	Loss-of-function, T-DNA insertion in exon 3	None	Hutchison <i>et al.</i> , 2006

Table 1. Continued

Gene abbreviation	Mutants	Molecular characterization	Phenotypes	References
	<i>ahp5-2</i>	Loss-of-function, T-DNA insertion in intron 4	None	Hutchison <i>et al.</i> , 2006
<i>AHP1, AHP2</i>	<i>ahp1 ahp2</i>		None	Hutchison <i>et al.</i> , 2006
<i>AHP1, AHP3</i>	<i>ahp1 ahp3</i>		None	Hutchison <i>et al.</i> , 2006
<i>AHP2, AHP3</i>	<i>ahp2 ahp3</i>		None under normal conditions, slightly reduced sensitivity to exogenous cytokinins	Hutchison <i>et al.</i> , 2006
<i>AHP2, AHP4</i>	<i>ahp2 ahp4</i>		None	Hutchison <i>et al.</i> , 2006
<i>AHP2, AHP5</i>	<i>ahp2 ahp5-2</i>		None	Hutchison <i>et al.</i> , 2006
<i>AHP3, AHP4</i>	<i>ahp3 ahp4</i>		None	Hutchison <i>et al.</i> , 2006
<i>AHP3, AHP5</i>	<i>ahp3 ahp5-2</i>		None	Hutchison <i>et al.</i> , 2006
<i>AHP4, AHP5</i>	<i>ahp4 ahp5-2</i>		None	Hutchison <i>et al.</i> , 2006
<i>AHP1, AHP5</i>	<i>ahp1 ahp5-1</i>		None	Hutchison <i>et al.</i> , 2006
<i>AHP1, AHP2, AHP3</i>	<i>ahp1 ahp2 ahp3</i>		None under normal conditions, reduced sensitivity to exogenous cytokinins	Hutchison <i>et al.</i> , 2006
<i>AHP2, AHP3, AHP4</i>	<i>ahp2 ahp3 ahp4</i>		None	Hutchison <i>et al.</i> , 2006
<i>AHP2 AHP3, AHP5</i>	<i>ahp2 ahp3 ahp5-2</i>		Short, narrow primary root	Hutchison <i>et al.</i> , 2006
<i>AHP1 AHP2, AHP3 AHP4</i>	<i>ahp1 ahp2 ahp3 ahp4</i>		None under normal conditions, reduced sensitivity to exogenous cytokinins	Hutchison <i>et al.</i> , 2006
<i>AHP2, AHP3, AHP4, AHP5</i>	<i>ahp2-1 ahp3 ahp5-2</i>		short, narrow primary root	Hutchison <i>et al.</i> , 2006
<i>AHP2, AHP3, AHP5</i>	<i>ahp2-1 ahp3 ahp4 ahp5-1</i>		Short, narrow primary root	Hutchison <i>et al.</i> , 2006
<i>AHP1, AHP2, AHP3, AHP4, AHP5</i>	<i>ahp1 ahp2-1 ahp3 ahp5-2</i>		Short, narrow primary root, impaired vascular development, delayed flowering, overall small size	Hutchison <i>et al.</i> , 2006; Deng <i>et al.</i> , 2010
<i>AHP1, AHP2, AHP3, AHP4, AHP5</i>	<i>ahp1 ahp2-2 ahp3 ahp4 ahp5-2</i>		Gametophytic lethality, rare escapers seedling lethal	Deng <i>et al.</i> , 2010
<i>AHP6</i>	<i>ahp6-1</i>	Nonsense mutation in first exon	Defects in vasculature: impaired protoxylem differentiation	Mähönen <i>et al.</i> , 2006a
<b>Type-A response regulators</b>				
<i>ARR3</i>	<i>arr3</i>	Loss-of-function, T-DNA insertion in 3'-UTR	None	To <i>et al.</i> , 2004; Salome <i>et al.</i> , 2006
<i>ARR4</i>	<i>arr4</i>	Hypomorphic, T-DNA insertion in exon 5	Mildly elongated petioles	To <i>et al.</i> , 2004; Salome <i>et al.</i> , 2006
<i>ARR5</i>	<i>arr5</i>	Hypomorphic, T-DNA insertion in exon 4	Reduced rosette size	To <i>et al.</i> , 2004; Salome <i>et al.</i> , 2006
<i>ARR6</i>	<i>arr6</i>	Hypomorphic, T-DNA insertion in intron 4	None	To <i>et al.</i> , 2004; Salome <i>et al.</i> , 2006
<i>ARR7</i>	<i>arr7-1</i>	Loss-of-function, T-DNA insertion in exon 3	None	Leibfried <i>et al.</i> , 2005
	<i>ARR7(RNAi)</i>	EtOH-inducible RNA interference transgene	None	Müller and Sheen, 2008
<i>ARR8</i>	<i>arr8</i>	Loss-of-function, T-DNA insertion in exon 1	Slightly reduced lateral root formation	To <i>et al.</i> , 2004; Salome <i>et al.</i> , 2006
<i>ARR9</i>	<i>arr9</i>	Hypomorphic, T-DNA insertion in intron 4	Slightly reduced lateral root formation	To <i>et al.</i> , 2004; Salome <i>et al.</i> , 2006
<i>ARR15</i>	<i>arr15-1</i>	Loss-of-function, T-DNA insertion in exon 5	None	Leibfried <i>et al.</i> , 2005
	<i>arr15-2</i>	Loss-of-function, T-DNA insertion in exon 1	None	Müller and Sheen, 2008

Table 1. Continued

Gene abbreviation	Mutants	Molecular characterization	Phenotypes	References
ARR16 ARR17				
ARR3, ARR4	<i>arr3 arr4</i>		Lengthen period of circadian clock, elongated petioles, increased sensitivity to exogenous cytokinins	To <i>et al.</i> , 2004; Salome <i>et al.</i> , 2006
ARR4, ARR5	<i>arr4 arr5</i>		Like <i>arr5</i> parent, increased sensitivity to exogenous cytokinins	To <i>et al.</i> , 2004; Salome <i>et al.</i> , 2006
ARR5, ARR6	<i>arr5 arr6</i>		None	To <i>et al.</i> , 2004; Salome <i>et al.</i> , 2006
ARR4, ARR6	<i>arr4 arr6</i>		Like <i>arr4</i> parent	To <i>et al.</i> , 2004; Salome <i>et al.</i> , 2006
ARR8, ARR9	<i>arr8 arr9</i>		Reduced lateral root formation, increased sensitivity to exogenous cytokinins	To <i>et al.</i> , 2004; Salome <i>et al.</i> , 2006
ARR7, ARR15	<i>arr7 arr15</i> <i>ARR7(RNAi) arr15</i>		Female gametophyte lethality Defects in embryonic root meristem, defects in phyllotaxis	Leibfried <i>et al.</i> , 2005 Zhao <i>et al.</i> , 2010; Müller and Sheen, 2008
ARR5, ARR6, ARR8, ARR9	<i>AlcA::AM7/15</i> <i>arr5 arr6 arr8 arr9</i>	EtOH-inducible microRNA	Defects in phyllotaxis None under normal conditions	Zhao <i>et al.</i> , 2010 To <i>et al.</i> , 2004; Salome <i>et al.</i> , 2006
ARR3, ARR4, ARR5, ARR6	<i>arr3 arr4 arr5 arr6</i>		Significantly elongated petioles, increased sensitivity to exogenous cytokinins, higher chlorophyll content	To <i>et al.</i> , 2004; Salome <i>et al.</i> , 2006
ARR3, ARR4, ARR8, ARR9	<i>arr3 arr4 arr8 arr9</i>		Markedly increased sensitivity to exogenous cytokinins	To <i>et al.</i> , 2004; Salome <i>et al.</i> , 2006
ARR3, ARR4, ARR5, ARR6, ARR8, ARR9	<i>arr3 arr4 arr5 arr6 arr8 arr9</i>		Elongated petioles, hypersensitive to exogenous cytokinins	To <i>et al.</i> , 2004; Salome <i>et al.</i> , 2006
ARR3, ARR4, ARR5, ARR6, ARR7, ARR8, ARR9	<i>arr3 arr4 arr5 arr6 arr7 arr8 arr9</i>		Defects in phyllotaxis	Leibfried <i>et al.</i> , 2005
<b>Type-B response regulators</b>				
ARR1	<i>arr1-1</i>	Loss-of-function, T-DNA insertion in intron 1	Slightly enlarged primary root	Sakai <i>et al.</i> , 2001
	<i>arr1-3</i>	Loss-of-function, T-DNA insertion in exon 5	None under normal conditions	Mason <i>et al.</i> , 2005; Argyros <i>et al.</i> , 2008
	<i>arr1-4</i>	Loss-of-function, T-DNA insertion in exon 3	None under normal conditions	Ishida <i>et al.</i> , 2008
ARR2	<i>arr2-4</i>	Loss-of-function, T-DNA insertion in exon 4	None under normal conditions, reduced pathogen resistance	Mason <i>et al.</i> , 2005; Choi <i>et al.</i> , 2010
	<i>arr2</i>	Loss-of-function, DS insertion in exon 1	Retarded growth, late flowering, reduced ethylene sensitivity	Hass <i>et al.</i> , 2004
ARR10	<i>arr10-2</i>	Loss-of-function, T-DNA insertion in intron 5	None under normal conditions	Mason <i>et al.</i> , 2005
	<i>arr10-5</i>	Loss-of-function, T-DNA insertion in exon 5	None under normal conditions	Ishida <i>et al.</i> , 2008; Argyros <i>et al.</i> , 2008
ARR11	<i>arr11-2</i>	Loss-of-function, T-DNA insertion exon 2	None under normal conditions	Mason <i>et al.</i> , 2005
ARR12	<i>arr12-1</i>	Loss-of-function, T-DNA insertion in exon 3	None under normal conditions	Mason <i>et al.</i> , 2005; Argyros <i>et al.</i> , 2008

Table 1. Continued

Gene abbreviation	Mutants	Molecular characterization	Phenotypes	References
<i>ARR14</i>	<i>arr14-1</i>	Loss-of-function, T-DNA insertion in exon 2	None under normal conditions	Ishida <i>et al.</i> , 2008
<i>ARR18</i>	<i>arr18-2</i>	Hypomorphic, T-DNA insertion in 5'-UTR	None under normal conditions	Mason <i>et al.</i> , 2005
<i>ARR19</i> <i>ARR20</i> <i>ARR21</i>		Loss-of-function, dSPM insertion in intron 3	None	Horák <i>et al.</i> , 2003
<i>ARR1, ARR10</i>	<i>arr1-1 arr10-2</i>		None under normal conditions, reduced sensitivity to exogenous cytokinins	Mason <i>et al.</i> , 2005
<i>ARR1, ARR11</i>	<i>arr1-1 arr11-2</i>		None under normal conditions, reduced sensitivity to exogenous cytokinins	Mason <i>et al.</i> , 2005
<i>ARR1, ARR18</i>	<i>arr1-3 arr18-2</i>		None under normal conditions, reduced sensitivity to exogenous cytokinins	Mason <i>et al.</i> , 2005
<i>ARR10, ARR11</i>	<i>arr10-2 arr11-2</i>		None under normal conditions, reduced sensitivity to exogenous cytokinins	Mason <i>et al.</i> , 2005
<i>ARR11, ARR18</i>	<i>arr11-2 arr18-2</i>		None under normal conditions, reduced sensitivity to exogenous cytokinins	Mason <i>et al.</i> , 2005
<i>ARR1, ARR10, ARR11</i>	<i>arr1-1 arr10-2</i>		None under normal conditions, reduced sensitivity to exogenous cytokinins	Mason <i>et al.</i> , 2005
<i>ARR1, ARR10, ARR12</i>	<i>arr1-3 arr10-2 arr12-1</i>		None under normal conditions, reduced sensitivity to exogenous cytokinins	Mason <i>et al.</i> , 2005
	<i>arr1-4 arr10-5 arr12-1</i>		Severe growth defect, resistance to exogenous cytokinins, vascular defects, reduced SAM	Ishida <i>et al.</i> , 2008
	<i>arr1-3 arr10-5 arr12-1</i>		Short narrow primary root, altered vascular development, reduced rosette size, reduced chlorophyll content, impaired response to exogenous cytokinins, increased seed size	Argyros <i>et al.</i> , 2008
<b>Type-C response regulators</b>				
<i>ARR22</i>	<i>arr22</i>	Loss-of-function, T-DNA insertion in exon 1	None	Gattolin <i>et al.</i> , 2006
	<i>arr22-2, arr22-3</i>	Loss-of-function, T-DNA insertion in intron 2	None	Horák <i>et al.</i> , 2008
<i>ARR24</i>	<i>arr24</i>	Loss-of-function, T-DNA insertions in exon	None	Gattolin <i>et al.</i> , 2006
<i>ARR22, ARR24</i>	<i>arr22 arr24</i>		None	Gattolin <i>et al.</i> , 2006

Riefler *et al.*, 2006), *AHPs* (Hutchison *et al.*, 2006; Deng *et al.*, 2010), type-A *ARRs* (Hutchison *et al.*, 2006; Salome *et al.*, 2006; To *et al.*, 2007), and type-B *ARRs* (Mason *et al.*, 2005; Argyros *et al.*, 2008; Ishida *et al.*, 2008). The results from these studies confirmed the extensive redundancy within each gene family: phenotype severity and insensitivity to cytokinin increased with the number of affected family members. In addition, gene-specific functions were uncovered (Table 1). In principle, these can be explained by the differential expression patterns, or by the specific protein functions of the genes involved. In the first scenario, loss of the family members with the highest expression levels in a given tissue is expected to result in the strongest phenotype. For example, *AHK4*'s functional contribution for the root system (Ueguchi *et al.*, 2001; Higuchi *et al.*, 2004; Nishimura *et al.*, 2004; Riefler *et al.*, 2006) reflects its relatively higher overall expression levels in root tissue (Ueguchi *et al.*, 2001; Higuchi *et al.*, 2004). In the transition zone of the primary root meristem however, *AHK3* expression (Nishimura *et al.*, 2004) and function prevails (Dello Ioio *et al.*, 2007). In the shoot apical meristem (SAM), *AHK2* and *AHK4*, but not *AHK3*, mediate cytokinin-dependent *WUSCHEL* (*WUS*) expression (Gordon *et al.*, 2009), which correlates with the low abundance of *AHK3* in the SAM (Nishimura *et al.*, 2004). Similarly, the strong phenotypes of a plant defective in three of the 11 type-B *ARRs*, *ARR1*, *ARR10*, and *ARR12* (Mason *et al.*, 2005; Yokoyama *et al.*, 2007; Ishida *et al.*, 2008) correlated with their relatively high and widespread expression (Mason *et al.*, 2004). Similarly, some of the type-A *ARR* mutant combinations exhibited specific phenotypes, which are consistent with the expression patterns of the affected genes. For example, *ARR8* and *ARR9* are expressed strongly throughout the root, and disrupting their loci affects lateral root number in seedlings but does not affect shoot development (To *et al.*, 2004). Disruption of *ARR7* and *ARR15* functions interferes with embryonic root meristem establishment in the early embryo (Müller and Sheen, 2008) and causes disturbed phyllotaxis in the SAM (Zhao *et al.*, 2010), in agreement with their unique expression patterns in these tissues. The reported female gametophyte lethality of an *arr7 arr15* double mutation (Leibfried *et al.*, 2005) could also reflect the expression patterns of *ARR7* and *ARR15* during this phase of development. The gene pairs *ARR8/ARR9* and *ARR7/ARR15* represent closely related sister genes (Fig. 2) and arose from the most recent *Arabidopsis* genome duplication (Vision *et al.*, 2000). Commonly, such sister genes share more redundant functions compared with more divergent pairs (Lynch and Conery, 2000). By analogy, analysing the missing double-mutant combinations of the *ARR* gene pairs *ARR16/ARR17*, *ARR19/ARR20*, or *ARR13/ARR21* (Fig. 2) could reveal interesting phenotypes. However, as an exception to the rule, the closely related type-B *ARR1* and *ARR2* genes (Fig. 2) share few functions (Hass *et al.*, 2004; Mason *et al.*, 2005; Choi *et al.*, 2010), despite their overlapping expression patterns (Mason *et al.*, 2004). Recently, the unique ability of *ARR2* to confer cytokinin-mediated

pathogen resistance has been mapped to the variable C-terminal domain beyond the conserved DNA-binding domain (Fig. 2). Via this portion of the protein, the transcription factor *ARR2* is recruited by *TGA3* to the *cis*-elements of the *PRI* promoter, leading to its transcriptional activation. Under the same conditions, *ARR1* did not interact with *TGA3* (Choi *et al.*, 2010). Gene-specific functions depending on the distinct biochemical functions of the affected genes were also described for other signalling components (see asterisks in Fig. 2). Similar to *AHK2*, *AHK3*, and *AHK4*, *CKII* codes for a hybrid kinase, which activates cytokinin signalling. However, it lacks the CHASE (cyclase/His kinase-associated sensing extracellular) domain involved in cytokinin binding (Fig. 2; Anantharaman and Aravind, 2001; Mougél and Zhulin, 2001). Indeed, *cki* plants still respond to exogenously applied cytokinins similar to the wild-type plants, supporting a specific function of *CKII*, which activates signalling independent of cytokinins (Hejátko *et al.*, 2009; Deng *et al.*, 2010). Characterization of the *wol* allele of *AHK4* revealed that phosphotransfer is bi-directional. Compared with wild-type *AHK4*, the *WOL* gene product has an amino acid change in the putative extracellular, cytokinin-binding region and lacks cytokinin binding activity, which reveals the inherent phosphatase activity of *AHK4* that normally depletes the circuitry of phosphoryl groups in the absence of ligands (Mähönen *et al.*, 2006b). *AHK2* and *AHK3* appear to lack a similar activity. *AHK3*, in turn, has been shown to exhibit unique functions in mediating cytokinin's function in leaf senescence (Kim *et al.*, 2006; Riefler *et al.*, 2006). Neither mutants of the other receptors, *AHK2* and *AHK4*, nor their overexpression affected leaf senescence (Kim *et al.*, 2006). Within the family of *AHPs*, *AHP6* stands out by lacking a conserved His residue in its receiver domain (Fig. 2), which renders it unable to accept an activating phosphoryl group (Mähönen *et al.*, 2006b). Hence, it was named pseudo *AHP*. *ahp6* mutant plants show defects in protoxylem differentiation, reflecting an increase in cytokinin signalling levels. *AHP6* negatively interferes with pathway activity, most likely by competing with *AHP1–5* for interaction with the activated receptors (Mähönen *et al.*, 2006a).

More gene-specific protein functions were uncovered by overexpression studies done *in planta* or heterologous systems. Compared with the analysis of different mutants, the use of ubiquitous promoters equalizes the expression patterns among the genes studied and, therefore, allows a direct comparison of the phenotypic effects caused by the coding sequences. For example, differential sensitivity of the cytokinin receptors *AKH4* and *AHK3* to biologically active cytokinins has been described (Yonekura-Sakakibara *et al.*, 2004; Spíchal *et al.*, 2004; Romanov *et al.*, 2006), opening the possibility of controlling the sensitivity to the available active cytokinins by regulating the expression pattern of the receptors. As the relative abundance of each receptor varies in different tissues, this possibility might be realized *in planta*. While overexpression of various type-A *ARRs* confirmed their negative role with respect to signalling activity (Fig. 1B; Hwang and Sheen, 2001; Osakabe *et al.*,

2002; Kiba *et al.*, 2003; Lee *et al.*, 2007; To *et al.*, 2007; Ren *et al.*, 2009), differences in phenotypes were also recorded. For example, overexpression of *ARR5* affected lateral root formation, whereas the closely related *ARR6* had little effect. Instead, it interfered with elongation of the primary root, which was not significantly changed by *ARR5* (Ren *et al.*, 2009). *ARR4* caused hypersensitivity to red light, and specifically interacted with Phytochrome B (Sweere *et al.*, 2001). *ARR16* appears unique among type-A family members in mediating cytokinin's function in leaf senescence (Ren *et al.*, 2009). These phenotypical differences are probably caused by the variable C-terminal domains of the type-A ARR (Fig. 2). As cytokinin-dependent protein stability has been reported to be differentially affecting different members (To and Kieber, 2008; Ren *et al.*, 2009), this mechanism may further contribute to the different phenotypes observed. Overexpression experiments with type-B ARRs resulted in increased sensitivity to cytokinin, consistent with their role as transcriptional activators in the signalling cascade (Fig. 1B; Hwang and Sheen, 2001; Sakai *et al.*, 2001; Imamura *et al.*, 2003; Tajima *et al.*, 2004). In addition, different type-B ARRs caused differences in phenotypes, both in the tissues affected and in the severity of the abnormalities (Imamura *et al.*, 2003; Hass *et al.*, 2004; Tajima *et al.*, 2004; Choi *et al.*, 2010). Since little difference was observed in the DNA-binding affinity of the different B-type ARRs *in vitro* (Sakai *et al.*, 2000; Hosoda *et al.*, 2002; Imamura *et al.*, 2003), and different B-type ARRs could all mediate transcriptional activation of a synthetic cytokinin reporter *in vivo* (Müller and Sheen, 2008), the unique functions of different type-B ARRs are probably encoded by their variable C-terminal extensions. This was exemplified with *ARR2* (Choi *et al.*, 2010), where the selection of cytokinin target genes is altered by the specific recruitment of DNA-binding cofactors. In summary, a number of gene-specific functions have been reported within families of the cytokinin signalling pathway, ranging from the receptors to the transcription factors. In cases where specificity is encoded by the protein sequences, the causative determinants in the protein sequence map to the variable amino acid residues of the different protein families, which mediate interaction with specific partners (Choi *et al.*, 2010), or exhibit altered biochemical activities (Mähönen *et al.*, 2006a, b). *In vitro*, the potential for differential protein interactions of cytokinin signalling genes has been uncovered by systematic screens (Dortay *et al.*, 2006, 2008). We are still far from a comprehensive view of how the individual protein signature of cytokinin signalling components contributes to signalling specificity. However, the identified specific functions provide a sound foundation to refine our understanding in a stepwise way. The contribution of differential expression to signalling specificity will be discussed further in the following sections.

#### *The expression level of signalling components affects the pathway activity*

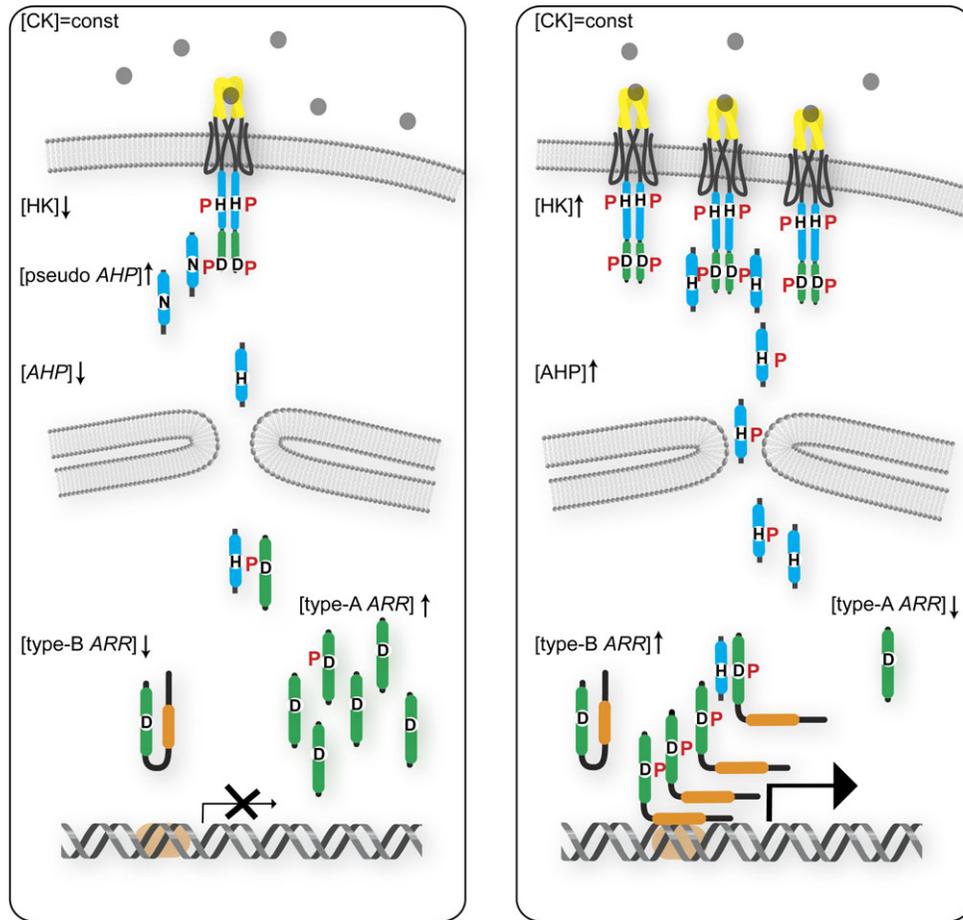
At least one member of a hybrid kinase, *AHP* and B-type *ARR* must be expressed beyond a minimal threshold level

for a cell to activate the signalling pathway. Increasing the expression levels of these positively acting components amplifies the signalling activity, while expression of the negatively acting type-A ARR and *AHP6* attenuates it (Fig. 3). Therefore, the efficiency of phosphotransfer correlates with the expression levels of signalling components, which represents a potential mechanism as to how to tailor the sensitivity to a given stimulus. Tissue-specificity, feedback regulation from cytokinin signalling and other signalling inputs are responsible for the spatio-temporal expression profiles of the signalling components. Feedback regulation has been documented for the expression of type-A ARRs and *AHP6*. Type-A ARRs represent immediately transcriptional target genes that negatively interfere with signalling activity. Such a negative feedback loop may serve to smooth-out fluctuations in signalling or to shut off pathway activity more abruptly after transient stimuli. Like type-A ARRs, *AHP6* suppresses pathway activity. However, its transcription is repressed by cytokinin signalling (Mähönen *et al.*, 2006a). This probably serves to generate sharper boundaries between signalling and non-signalling domains in a tissue.

#### *Spatiotemporal expression map of signalling components defines a sensitivity landscape*

In addition to feedback regulation, the complex expression patterns of hybrid kinases, *AHPs*, and *ARRs* suggest elaborate transcription regulation, which integrates tissue-specific, and multiple signalling inputs. Thus, a picture emerges where expression of cytokinin signalling components predefines a spatiotemporal map of signalling sensitivity. This allows localized signal amplification and attenuation, depending on the functional requirements.

Recent studies of cytokinin function at the cellular resolution have opened the door to study the functional relevance as to how cytokinin output is influenced by the expression profiles of signalling genes (Fig. 4; Leibfried *et al.*, 2005; Müller and Sheen, 2008; Gordon *et al.*, 2009; Moubayidin *et al.*, 2010; Zhao *et al.*, 2010). While knowledge of all present signalling genes in a given cell defines its sensitivity and competence, the actual signalling response ultimately depends on the local concentration of active cytokinins, which is difficult to determine, due to the small size of active ligands and their diversity. Thus, the key to analysing cytokinin's function in the context of the embryonic root-meristem specification was the construction of a synthetic promoter, which does not rely on secondary signalling or tissue-specific information. Rather, its activity reflects the cytokinin signalling output in the nucleus, that is, transcriptional activation mediated by type-B ARRs (Müller and Sheen, 2008). Reporter activity was observed in the hypophysis, precursor of the root stem cell system. Upon asymmetric cell division of the hypophysis, the resulting basal cell lineage down-regulated cytokinin output, while the apical cell maintained activity. This differential signalling output, which is essential for the development of the nascent root meristem, depends on auxin to activate the

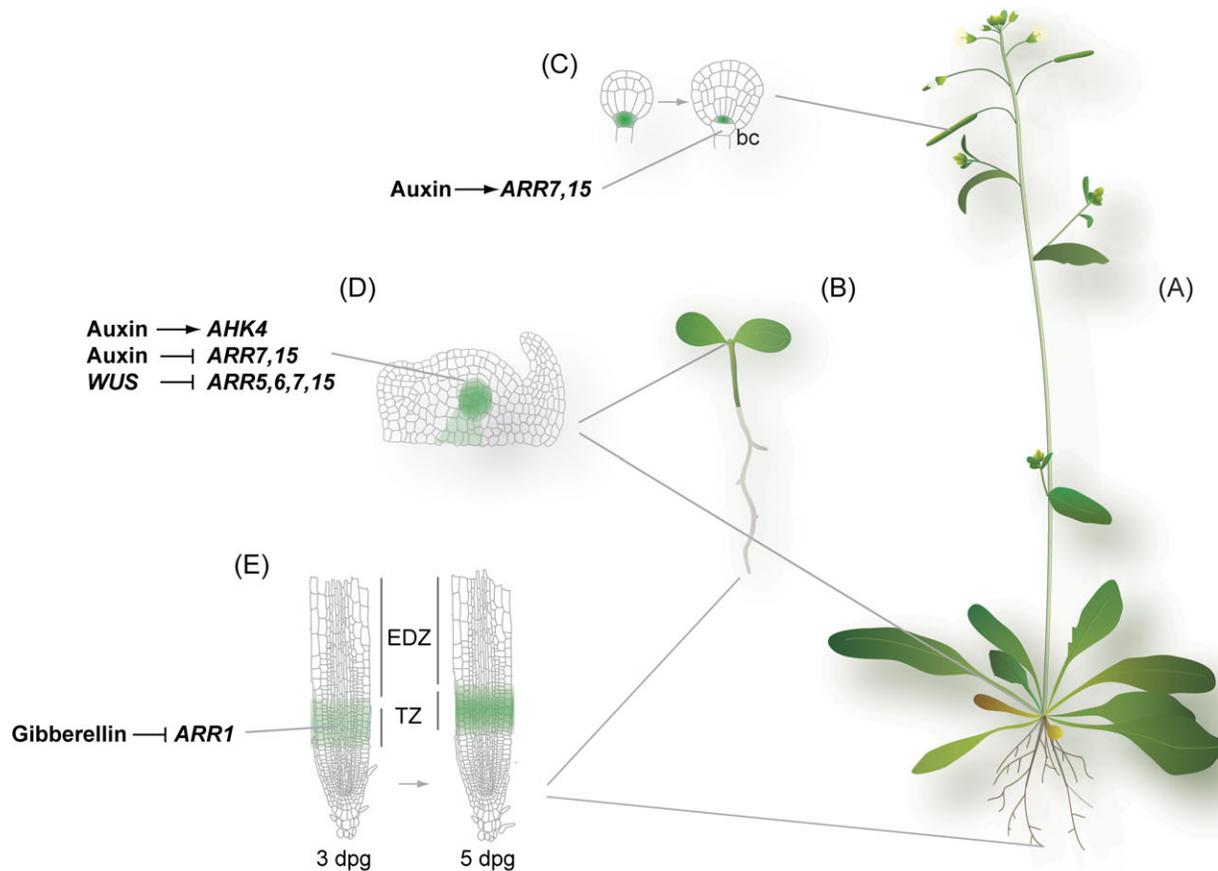


**Fig. 3.** Cartoon to illustrate how different expression levels of intracellular cytokinin signalling components affects the signalling activity, given a constant concentration of active ligands. On the left, signalling output is blocked due to prevalence of negative regulators: pseudo AHP6 and type-A ARR. On the right, signalling output is maximized due to up-regulation of positive-acting signalling components: HKs, AHPs, type-B ARRs. Cytokinins are indicated as grey circles. Up-facing arrows indicate high concentrations, down-facing arrows low concentrations. Conserved domains are depicted as in Fig. 2.

transcription of the type-A *ARR7* and *ARR15* directly (Fig. 4C). Auxin signalling thus interferes with cytokinin signalling in a defined domain by inducing negative regulators, which suppresses the efficiency of phosphorelay. An analogous mechanism operates in the shoot apical meristem (Fig. 4D). However, interestingly, the relationship is reversed: here, auxin represses the transcription of *ARR7* and *ARR15*, leading to an increase in cytokinin signalling activity. Again, this cross-talk appears functionally relevant as interfering with *ARR7* and *ARR15* levels causes irregularities in phyllotaxis, the ordered arrangement of lateral shoots (Zhao *et al.*, 2010). In addition, *WUS* directly attenuates transcription of type-A *ARR5*, *ARR6*, *ARR7*, and *ARR15* (Leibfried *et al.*, 2005), again enhancing cytokinin-signalling activity. In the same context, an increase in receptor levels further contributes to increased perception in a spatially defined domain (Gordon *et al.*, 2009). Therefore, in the shoot apical meristem, both a decrease in the abundance of negative regulators (Leibfried *et al.*, 2005; Zhao *et al.*, 2010), and an increase in expression of a cytokinin receptor (Gordon *et al.*, 2009), a positive regulator, contributes to enhance the sensitivity to cytoki-

nins. Cytokinin signalling in the transition zone of the adult root meristem counteracts proliferation by promoting differentiation (Dello Iorio *et al.*, 2007). Thus, exact signalling levels are critical for establishing the balance between growth and differentiation. During the early phases, when net growth of the root is required, the proliferation-inducing phytohormone Gibberellin selectively represses the transcription of type-B *ARR1*, hereby lowering the sensitivity to available cytokinins and hence signalling levels (Fig. 4E). At the later stages, when Gibberellin levels decrease, *ARR1* transcription and, consequently, cytokinin signalling increases, which tips the balance towards differentiation (Moubayidin *et al.*, 2010). Here, competence to respond to cytokinin is regulated by controlling the expression of a type-B *ARR*. These studies have revealed the functional importance of modulating pathway activity by controlling the expression levels of signalling components.

More detailed studies will probably follow to demonstrate how other signalling pathways determine the sensitivity landscape by amplifying or attenuating the cytokinin response. During female gametophyte development, cytokinin-signalling levels are controlled by the hybrid kinase



**Fig. 4.** The regulation of cytokinin signalling components affects the signalling output in different plant organs. Cartoons of an adult *Arabidopsis* plant (A), and a seedling (B). Schematic views of early embryos at the globular and transition stage (C), the shoot apical meristem (D), and the primary root (E) are drawn on the left. Cytokinin output is indicated in green, based on the expression of the synthetic TCS reporter in (C) (Müller and Sheen, 2008) and (D) (Zhao *et al.*, 2010), or inferred from the expression patterns of *ARR1* and *ARR12* and phenotypic analysis of the corresponding mutants (Moubayidin *et al.*, 2010) in (D). (C) Down-regulation of cytokinin output in the basal cell (bc) of a transition-stage embryo is caused by auxin, which induces the transcription of *ARR7* and *ARR15* (Müller and Sheen, 2008). In the shoot meristem (D), several mechanisms operate in parallel to up-regulate cytokinin sensitivity: auxin stimulates expression of *AHK4* (Gordon *et al.*, 2009), and represses transcription of *ARR7* and *ARR15* (Zhao *et al.*, 2010), while *WUS* represses transcription of *ARR5*, *ARR6*, *ARR7*, and *ARR15* (Leibfried *et al.*, 2005). In the primary root (E), Gibberellin signalling represses *ARR1* expression at the early stages (3 days post germination, dpg). Later, around 5 dpg, the mechanism is released, allowing expression of *ARR1* and increased cytokinin signalling output (Moubayidin *et al.*, 2010). TZ, transition zone; EDZ, elongation and differentiation zone. Refer also to the body text for further explanations.

*CKII* (Pischke *et al.*, 2002; Hejátko *et al.*, 2003), independent of the bona fide cytokinin receptors *AHK2*, *AHK3*, and *AHK4* (Deng *et al.*, 2010). *CKII* activates cytokinin signalling independent of cytokinins (Hwang and Sheen, 2001; Yamada *et al.*, 2001; Hejátko *et al.*, 2009; Deng *et al.*, 2010). Accordingly, pathway activity depends on the transcriptional profile of *CKII*, and it will be interesting to identify the signals responsible. One candidate signal is auxin, which has been reported to be involved in patterning of the embryo sac (Pagnussat *et al.*, 2009). By inducing *CKII* expression, these signals can directly activate the cytokinin-signalling pathway, bypassing the need of cytokinins. Cytokinin's function in root gravitropism could, potentially, also be influenced by auxin (Aloni *et al.*, 2004). Transcription of the type-C ARR *ARR22* is induced by wounding (Gattolin *et al.*, 2006), which could reflect an

additional case of how cytokinin output is determined by other signals. Recently, GeBP and GeBP-like transcription factors were identified that influence the cytokinin response by indirectly affecting the expression levels of type-A *ARRs* (Chevalier *et al.*, 2008). The concept of organizing cross-talk among hormone signalling pathways by controlling the expression levels of key signalling components is further exemplified by several well-documented cases where cytokinin signalling influences other signalling pathways (Laplaze *et al.*, 2007; Dello Ioio *et al.*, 2008; Ruzicka *et al.*, 2009).

The cellular response to cytokinin signalling qualitatively differs in the examples discussed above. In the nascent root meristem (Müller and Sheen, 2008) and during female gametophyte development (Pischke *et al.*, 2002; Hejátko *et al.*, 2003; Deng *et al.*, 2010), interfering with cytokinin function affects cell specification while, in the root,

cytokinin has been shown to counteract auxin-promoted proliferation in the transition zone (Dello Ioio *et al.*, 2008). In the shoot meristem, cytokinin's role is to maintain the size and function of the stem-cell pool (To and Kieber, 2008; Gordon *et al.*, 2009; Werner and Schmülling, 2009; Zhao *et al.*, 2010). How can the same signalling pathway elicit these different responses? As discussed above, the specific set of cytokinin signalling proteins present in the cell may affect the signalling outcome. Along with the type-B ARR transcription factors, CYTOKININ RESPONSE FACTORS (CRF) have been reported to control a subset of immediate-early cytokinin target genes, further increasing the specificity of the signalling response (Rashotte *et al.*, 2006). In addition, the cellular status of the signal-receiving cell can affect how a signal is interpreted. In the case of cytokinin signalling, cytokinin-responsive promoters may rely on secondary regulatory input to confer transcriptional activation. For example, while transcription of type-A ARRs is sensitive to cytokinin, the transcription patterns only partly overlap, reflecting the dependence on additional input (To *et al.*, 2004; Leibfried *et al.*, 2005). Transcriptome changes in response to exogenous cytokinin treatment were characterized in different settings (Che *et al.*, 2002; Hoth *et al.*, 2003; Rashotte *et al.*, 2003; Brenner *et al.*, 2005). The overlap among cytokinin-target genes between the different experiments was relatively small, providing further arguments that, in addition to cytokinin signalling, tissue- and context-specific inputs are important. Transcription control of the *ARR7* and *ARR15* genes demonstrates how the cellular context influences promoter activity: the same *cis*-regulatory sequence integrates activating input by the auxin pathway in the embryonic root meristem (Müller and Sheen, 2008), and repressive auxin input in the shoot meristem (Zhao *et al.*, 2010). Future analyses aimed at characterizing the relevant cytokinin target genes during female gametophyte development, root meristem specification and maintenance, and shoot meristem homeostasis will provide the necessary basis to address further the question of target-gene specificity in well-defined developmental contexts at high resolution.

## Concluding remarks

Signalling circuitries allow cells to change the gene expression profile specifically in response to cues originating from their outside. The limited number of signalling system contrasts with the numerous and diverse responses they elicit. On the one hand, gene-specific functions, both coded by *cis*-regulatory and coding sequence, contribute to specific responses. This also applies to the cytokinin signalling pathway—its relatively simple core pathway logic becomes increasingly complex with the multiple family members, each with a complex expression pattern and the potential to interact with diverse partners. On the other hand, the cellular context of signalling affects the cellular response triggered. Specifically, the integration of tissue-specific information and other signals by the *cis*-regulatory regions of

potential target genes renders transcriptome changes context-dependent. Progress made in the last decade in the understanding of the cytokinin signalling pathway, and how it is specifically implemented in the developmental context, has been remarkable, and will continue at a fast pace. Recent studies (Mähönen *et al.*, 2006a; Dello Ioio *et al.*, 2008; Müller and Sheen, 2008; Gordon *et al.*, 2009; Hejátko *et al.*, 2009; Deng *et al.*, 2010; Moubayidin *et al.*, 2010; Zhao *et al.*, 2010) have demonstrated the importance of precisely tuning the levels of cytokinin signalling during development, which results in an elaborate spatiotemporal signalling landscape. The main focus here was on work using the reference plant *Arabidopsis*, however, increasing effort is being devoted to study cytokinin signalling in crop plants (Giulini *et al.*, 2004; Yonekura-Sakakibara *et al.*, 2004; Ito and Kurata, 2006) and plants with different life cycles, which allows the role of cytokinin in the evolution of the plant body plan to be studied (Pils and Heyl, 2009; Hellmann *et al.*, 2010).

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## References

- Aloni R, Langhans M, Aloni E, Ullrich CI. 2004. Role of cytokinin in the regulation of root gravitropism. *Planta* **220**, 177–182.
- Amasino R. 2005. 1955: Kinetin arrives: the 50th anniversary of a new plant hormone. *Plant Physiology* **138**, 1177–1184.
- Anantharaman V, Aravind L. 2001. The CHASE domain: a predicted ligand-binding module in plant cytokinin receptors and other eukaryotic and bacterial receptors. *Trends in Biochemical Sciences* **26**, 579–582.
- Argyros RD, Mathews DE, Chiang YH, Palmer CM, Thibault DM, Etheridge N, Argyros DA, Mason MG, Kieber JJ, Schaller GE. 2008. Type-B response regulators of *Arabidopsis* play key roles in cytokinin signalling and plant development. *The Plant Cell* **20**, 2102–2116.
- Brenner WG, Romanov GA, Köllmer I, Bürkle L, Schmülling T. 2005. Immediate-early and delayed cytokinin response genes of *Arabidopsis thaliana* identified by genome-wide expression profiling reveal novel cytokinin-sensitive processes and suggest cytokinin action through transcriptional cascades. *The Plant Journal* **44**, 314–333.
- Che P, Gingerich DJ, Lall S, Howell SH. 2002. Global and hormone-induced gene expression changes during shoot development in *Arabidopsis*. *The Plant Cell* **14**, 2771–2785.
- Chevalier F, Perazza D, Laporte F, Le Hénanff G, Hornitschek P, Bonneville JM, Herzog M, Vachon G. 2008. GeBP and GeBP-like proteins are noncanonical leucine-zipper transcription factors that regulate cytokinin response in *Arabidopsis*. *Plant Physiology* **146**, 1142–1154.

- Choi J, Huh SU, Kojima M, Sakakibara H, Paek KH, Hwang I.** 2010. The cytokinin-activated transcription factor ARR2 promotes plant immunity via TGA3/NPR1-dependent salicylic acid signalling in *Arabidopsis*. *Developmental Cell* **19**, 284–295.
- Cline M, Wessel' T, Iwamura H.** 1997. Cytokinin/auxin control of apical dominance in *Ipomoea nil*. *Plant and Cell Physiology* **38**, 639–667.
- D'Agostino IB, Deruere J, Kieber JJ.** 2000. Characterization of the response of the *Arabidopsis* response regulator gene family to cytokinin. *Plant Physiology* **124**, 1706–1717.
- Davidson EH, Erwin DH.** 2006. Gene regulatory networks and the evolution of animal body plans. *Science* **311**, 796–800.
- Dello Ioio R, Linhares FS, Scacchi E, Casamitjana-Martinez E, Heidstra R, Costantino P, Sabatini S.** 2007. Cytokinins determine *Arabidopsis* root-meristem size by controlling cell differentiation. *Current Biology* **17**, 678–682.
- Dello Ioio R, Nakamura K, Moubayidin L, Perilli S, Taniguchi M, Morita MT, Aoyama T, Costantino P, Sabatini S.** 2008. A genetic framework for the control of cell division and differentiation in the root meristem. *Science* **322**, 1380–1384.
- Deng Y, Dong H, Mu J, Ren B, Zheng B, Ji Z, Yang WC, Liang Y, Zuo J.** 2010. *Arabidopsis* histidine kinase *CK1* acts upstream of histidine phosphotransfer proteins to regulate female gametophyte development and vegetative growth. *The Plant Cell* **22**, 1232–1248.
- Dortay H, Gruhn N, Pfeifer A, Schwerdtner M, Schmölling T, Heyl A.** 2008. Toward an interaction map of the two-component signalling pathway of *Arabidopsis thaliana*. *Journal of Proteome Research* **7**, 3649–3660.
- Dortay H, Mehnert N, Bürkle L, Schmölling T, Heyl A.** 2006. Analysis of protein interactions within the cytokinin-signalling pathway of *Arabidopsis thaliana*. *FEBS Journal* **273**, 4631–4644.
- Ferreira FJ, Kieber JJ.** 2005. Cytokinin signalling. *Current Opinion in Plant Biology* **8**, 518–525.
- Gan S, Amasino RM.** 1995. Inhibition of leaf senescence by autoregulated production of cytokinin. *Science* **270**, 1986–1988.
- Gattolin S, Alandete-Saez M, Elliott K, Gonzalez-Carranza Z, Naomab E, Powell C, Roberts JA.** 2006. Spatial and temporal expression of the response regulators *ARR22* and *ARR24* in *Arabidopsis thaliana*. *Journal of Experimental Botany* **57**, 4225–4233.
- Giulini A, Wang J, Jackson D.** 2004. Control of phyllotaxy by the cytokinin-inducible response regulator homologue *ABPHYL1*. *Nature* **430**, 1031–1034.
- Gordon SP, Chickarmane VS, Ohno C, Meyerowitz EM.** 2009. Multiple feedback loops through cytokinin signalling control stem cell number within the *Arabidopsis* shoot meristem. *Proceedings of the National Academy of Sciences, USA* **106**, 16529–16534.
- Hass C, Lohrmann J, Albrecht V, et al.** 2004. The response regulator 2 mediates ethylene signalling and hormone signal integration in *Arabidopsis*. *EMBO Journal* **23**, 3290–3302.
- Hejátko J, Ryu H, Kim GT, et al.** 2009. The histidine kinases *CYTOKININ-INDEPENDENT1* and *Arabidopsis HISTIDINE KINASE2* and 3 regulate vascular tissue development in *Arabidopsis* shoots. *The Plant Cell* **21**, 2008–2021.
- Hejátko J, Pernisova M, Eneva T, Palme K, Brzobohatý B.** 2003. The putative sensor histidine kinase *CK1* is involved in female gametophyte development in *Arabidopsis*. *Molecular Genetics and Genomics* **269**, 443–453.
- Hellmann E, Gruhn N, Heyl A.** 2010. The more, the merrier: cytokinin signalling beyond *Arabidopsis*. *Plant Signalling and Behavior* **5**, (in press).
- Higuchi M, Pischke MS, Mahönen AP, et al.** 2004. In planta functions of the *Arabidopsis* cytokinin receptor family. *Proceedings of the National Academy of Sciences, USA* **101**, 8821–8826.
- Horák J, Grefen C, Berendzen KW, Hahn A, Stierhof YD, Stadelhofer B, Stahl M, Koncz C, Harter K.** 2008. The *Arabidopsis thaliana* response regulator *ARR22* is a putative AHP phospho-histidine phosphatase expressed in the chalaza of developing seeds. *BMC Plant Biology* **8**, 77.
- Hosoda K, Imamura A, Katoh E, Hatta T, Tachiki M, Yamada H, Mizuno T, Yamazaki T.** 2002. Molecular structure of the GARP family of plant Myb-related DNA binding motifs of the *Arabidopsis* response regulators. *The Plant Cell* **14**, 2015–2029.
- Hoth S, Ikeda Y, Morgante M, Wang X, Zuo J, Hanafey MK, Gaasterland T, Tingey SV, Chua NH.** 2003. Monitoring genome-wide changes in gene expression in response to endogenous cytokinin reveals targets in *Arabidopsis thaliana*. *FEBS Letters* **554**, 373–380.
- Hutchison CE, Li J, Argueso C, et al.** 2006. The *Arabidopsis* histidine phosphotransfer proteins are redundant positive regulators of cytokinin signalling. *The Plant Cell* **18**, 3073–3087.
- Hwang I, Chen HC, Sheen J.** 2002. Two-component signal transduction pathways in *Arabidopsis*. *Plant Physiology* **129**, 500–515.
- Hwang I, Sheen J.** 2001. Two-component circuitry in *Arabidopsis* cytokinin signal transduction. *Nature* **413**, 383–389.
- Imamura A, Hanaki N, Nakamura A, Suzuki T, Taniguchi M, Kiba T, Ueguchi C, Sugiyama T, Mizuno T.** 1999. Compilation and characterization of *Arabidopsis thaliana* response regulators implicated in His-Asp phosphorelay signal transduction. *Plant and Cell Physiology* **40**, 733–742.
- Imamura A, Kiba T, Tajima Y, Yamashino T, Mizuno T.** 2003. In vivo and in vitro characterization of the *ARR11* response regulator implicated in the His-to-Asp phosphorelay signal transduction in *Arabidopsis thaliana*. *Plant and Cell Physiology* **44**, 122–131.
- Inoue T, Higuchi M, Hashimoto Y, Seki M, Kobayashi M, Kato T, Tabata S, Shinozaki K, Kakimoto T.** 2001. Identification of *CRE1* as a cytokinin receptor from *Arabidopsis*. *Nature* **409**, 1060–1063.
- Ishida K, Yamashino T, Yokoyama A, Mizuno T.** 2008. Three type-B response regulators, *ARR1*, *ARR10* and *ARR12*, play essential but redundant roles in cytokinin signal transduction throughout the life cycle of *Arabidopsis thaliana*. *Plant and Cell Physiology* **49**, 47–57.
- Ito Y, Kurata N.** 2006. Identification and characterization of cytokinin-signalling gene families in rice. *Gene* **382**, 57–65.
- Jeon J, Kim NY, Kim S, Kang NY, Novak O, Ku SJ, Cho C, Lee DJ, Lee EJ, Strnad M, Kim J.** 2010. A subset of cytokinin two-component signalling system plays a role in cold temperature stress response in *Arabidopsis*. *Journal of Biological Chemistry* **285**, 23371–23386.

- Kakimoto T.** 1996. CK11, a histidine kinase homolog implicated in cytokinin signal transduction. *Science* **274**, 982–985.
- Katoh K, Toh H.** 2008. Recent developments in the MAFFT multiple sequence alignment program. *Briefings in Bioinformatics* **9**, 286–298.
- Kiba T, Aoki K, Sakakibara H, Mizuno T.** 2004. *Arabidopsis* response regulator, ARR22, ectopic expression of which results in phenotypes similar to the *wol* cytokinin-receptor mutant. *Plant and Cell Physiology* **45**, 1063–1077.
- Kiba T, Yamada H, Sato S, Kato T, Tabata S, Yamashino T, Mizuno T.** 2003. The type-A response regulator, ARR15, acts as a negative regulator in the cytokinin-mediated signal transduction in *Arabidopsis thaliana*. *Plant and Cell Physiology* **44**, 868–874.
- Kim HJ, Ryu H, Hong SH, Woo HR, Lim PO, Lee IC, Sheen J, Nam HG, Hwang I.** 2006. Cytokinin-mediated control of leaf longevity by AHK3 through phosphorylation of ARR2 in *Arabidopsis*. *Proceedings of the National Academy of Sciences, USA* **103**, 814–819.
- Kudo T, Kiba T, Sakakibara H.** 2010. Metabolism and long-distance translocation of cytokinins. *Journal of Integrative Plant Biology* **52**, 53–60.
- Laplace L, Benková E, Casimiro I, et al.** 2007. Cytokinins act directly on lateral root founder cells to inhibit root initiation. *The Plant Cell* **19**, 3889–3900.
- Lee DJ, Park JY, Ku SJ, Ha YM, Kim S, Kim MD, Oh MH, Kim J.** 2007. Genome-wide expression profiling of *Arabidopsis* RESPONSE REGULATOR 7 (ARR7) overexpression in cytokinin response. *Molecular Genetics and Genomics* **277**, 115–137.
- Leibfried A, To JP, Busch W, Stehling S, Kehle A, Demar M, Kieber JJ, Lohmann JU.** 2005. WUSCHEL controls meristem function by direct regulation of cytokinin-inducible response regulators. *Nature* **438**, 1172–1175.
- Lynch M, Conery JS.** 2000. The evolutionary fate and consequences of duplicate genes. *Science* **290**, 1151–1155.
- Mähönen AP, Bishopp A, Higuchi M, Nieminen KM, Kinoshita K, Tormakangas K, Ikeda Y, Oka A, Kakimoto T, Helariutta Y.** 2006a. Cytokinin signalling and its inhibitor AHP6 regulate cell fate during vascular development. *Science* **311**, 94–98.
- Mähönen AP, Higuchi M, Tormakangas K, Miyawaki K, Pischke MS, Sussman MR, Helariutta Y, Kakimoto T.** 2006b. Cytokinins regulate a bidirectional phosphorelay network in *Arabidopsis*. *Current Biology* **16**, 1116–1122.
- Mähönen AP, Bonke M, Kauppinen L, Riikonen M, Benfey PN, Helariutta Y.** 2000. A novel two-component hybrid molecule regulates vascular morphogenesis of the *Arabidopsis* root. *Genes and Development* **14**, 2938–2943.
- Mason MG, Li J, Mathews DE, Kieber JJ, Schaller GE.** 2004. Type-B response regulators display overlapping expression patterns in *Arabidopsis*. *Plant Physiology* **135**, 927–937.
- Mason MG, Mathews DE, Argyros DA, Maxwell BB, Kieber JJ, Alonso JM, Ecker JR, Schaller GE.** 2005. Multiple type-B response regulators mediate cytokinin signal transduction in *Arabidopsis*. *The Plant Cell* **17**, 3007–3018.
- Meyerowitz EM.** 2002. Plants compared to animals: the broadest comparative study of development. *Science* **295**, 1482–1485.
- Miller CO.** 1956. Similarity of some Kinetin and red light effects. *Plant Physiology* **31**, 318–319.
- Miller CO.** 1958. The relationship of the Kinetin and red-light promotions of lettuce seed germination. *Plant Physiology* **33**, 115–117.
- Miller CO, Skoog F, Von Saltza MH, Strong F.** 1955. Kinetin, a cell division factor from deoxyribonucleic acid. *Journal of the American Chemical Society* **77**, 1392.
- Mizuno T.** 2005. Two-component phosphorelay signal transduction systems in plants: from hormone responses to circadian rhythms. *Bioscience, Biotechnology, and Biochemistry* **69**, 2263–2276.
- Mok DW, Mok MC.** 2001. Cytokinin metabolism and action. *Annual Review of Plant Physiology and Plant Molecular Biology* **52**, 89–118.
- Moubayidin L, Perilli S, Dello Iorio R, Di Mambro R, Costantino P, Sabatini S.** 2010. The rate of cell differentiation controls the *Arabidopsis* root meristem growth phase. *Current Biology* **20**, 1138–1143.
- Mougel C, Zhulin IB.** 2001. CHASE: an extracellular sensing domain common to transmembrane receptors from prokaryotes, lower eukaryotes and plants. *Trends in Biochemical Sciences* **26**, 582–584.
- Müller B, Sheen J.** 2008. Cytokinin and auxin interaction in root stem-cell specification during early embryogenesis. *Nature* **453**, 1094–1097.
- Nishimura C, Ohashi Y, Sato S, Kato T, Tabata S, Ueguchi C.** 2004. Histidine kinase homologs that act as cytokinin receptors possess overlapping functions in the regulation of shoot and root growth in *Arabidopsis*. *The Plant Cell* **16**, 1365–1377.
- Osakabe Y, Miyata S, Urao T, Seki M, Shinozaki K, Yamaguchi-Shinozaki K.** 2002. Overexpression of *Arabidopsis* response regulators, ARR4/ATRR1/IBC7 and ARR8/ATRR3, alters cytokinin responses differentially in the shoot and in callus formation. *Biochemical and Biophysical Research Communications* **293**, 806–815.
- Pagnussat GC, Alandete-Saez M, Bowman JL, Sundaresan V.** 2009. Auxin-dependent patterning and gamete specification in the *Arabidopsis* female gametophyte. *Science* **324**, 1684–1689.
- Perilli S, Moubayidin L, Sabatini S.** 2010. The molecular basis of cytokinin function. *Current Opinion in Plant Biology* **13**, 21–26.
- Pils B, Heyl A.** 2009. Unraveling the evolution of cytokinin signalling. *Plant Physiology* **151**, 782–791.
- Pischke MS, Jones LG, Otsuga D, Fernandez DE, Drews GN, Sussman MR.** 2002. An *Arabidopsis* histidine kinase is essential for megagametogenesis. *Proceedings of the National Academy of Sciences, USA* **99**, 15800–15805.
- Punwani JA, Hutchison CE, Schaller GE, Kieber JJ.** 2010. The subcellular distribution of the *Arabidopsis* histidine phosphotransfer proteins is independent of cytokinin signalling. *The Plant Journal* **62**, 473–482.
- Rashotte AM, Carson SD, To JP, Kieber JJ.** 2003. Expression profiling of cytokinin action in *Arabidopsis*. *Plant Physiology* **132**, 1998–2011.
- Rashotte AM, Mason MG, Hutchison CE, Ferreira FJ, Schaller GE, Kieber JJ.** 2006. A subset of *Arabidopsis* AP2 transcription factors mediates cytokinin responses in concert with

a two-component pathway. *Proceedings of the National Academy of Sciences, USA* **103**, 11081–11085.

**Ren B, Liang Y, Deng Y, Chen Q, Zhang J, Yang X, Zuo J.** 2009. Genome-wide comparative analysis of type-A *Arabidopsis* response regulator genes by overexpression studies reveals their diverse roles and regulatory mechanisms in cytokinin signalling. *Cell Research* **19**, 1178–1190.

**Richmond AE, Lang A.** 1957. Effect of Kinetin on protein content and survival of detached *Xanthium* leaves. *Science* **125**, 650–651.

**Riefler M, Novak O, Strnad M, Schmülling T.** 2006. *Arabidopsis* cytokinin receptor mutants reveal functions in shoot growth, leaf senescence, seed size, germination, root development, and cytokinin metabolism. *The Plant Cell* **18**, 40–54.

**Romanov GA, Lomin SN, Schmülling T.** 2006. Biochemical characteristics and ligand-binding properties of *Arabidopsis* cytokinin receptor AHK3 compared to CRE1/AHK4 as revealed by a direct binding assay. *Journal of Experimental Botany* **57**, 4051–4058.

**Ruzicka K, Simaskova M, Duclercq J, Petrasek J, Zazimalova E, Simon S, Friml J, Van Montagu MC, Benková E.** 2009. Cytokinin regulates root meristem activity via modulation of the polar auxin transport. *Proceedings of the National Academy of Sciences, USA* **106**, 4284–4289.

**Sakai H, Honma T, Aoyama T, Sato S, Kato T, Tabata S, Oka A.** 2001. ARR1, a transcription factor for genes immediately responsive to cytokinins. *Science* **294**, 1519–1521.

**Sakai H, Aoyama T, Oka A.** 2000. *Arabidopsis* ARR1 and ARR2 response regulators operate as transcriptional activators. *The Plant Journal* **24**, 703–711.

**Salome PA, To JP, Kieber JJ, McClung CR.** 2006. *Arabidopsis* response regulators ARR3 and ARR4 play cytokinin-independent roles in the control of circadian period. *The Plant Cell* **18**, 55–69.

**Saitou N, Nei M.** 1987. The Neighbor-Joining method: a new method for reconstructing phylogenetic trees. *Molecular Biology and Evolution* **4**, 406–425.

**Santner A, Calderon-Villalobos LI, Estelle M.** 2009. Plant hormones are versatile chemical regulators of plant growth. *Nature Chemical Biology* **5**, 301–307.

**Skoog F, Miller CO.** 1957. Chemical regulation of growth and organ formation in plant tissues cultured *in vitro*. *Symposia of the Society for Experimental Biology* **54**, 118–130.

**Spíchal L, Rakova NY, Riefler M, Mizuno T, Romanov GA, Strnad M, Schmülling T.** 2004. Two cytokinin receptors of *Arabidopsis thaliana*, CRE1/AHK4 and AHK3, differ in their ligand specificity in a bacterial assay. *Plant and Cell Physiology* **45**, 1299–1305.

**Suzuki T, Miwa K, Ishikawa K, Yamada H, Aiba H, Mizuno T.** 2001. The *Arabidopsis* sensor His-kinase, AHK4, can respond to cytokinins. *Plant and Cell Physiology* **42**, 107–113.

**Suzuki T, Sakurai K, Imamura A, Nakamura A, Ueguchi C, Mizuno T.** 2000. Compilation and characterization of histidine-containing phosphotransmitters implicated in His-to-Asp phosphorelay in plants: AHP signal transducers of *Arabidopsis thaliana*. *Bioscience, Biotechnology, and Biochemistry* **64**, 2486–2489.

**Swarbreck D, Wilks C, Lamesch P, et al.** 2008. The *Arabidopsis* Information Resource (TAIR): gene structure and function annotation. *Nucleic Acids Research* **36**, D1009–D1014.

**Sweere U, Eichenberg K, Lohrmann J, Mira-Rodado V, Baurle I, Kudla J, Nagy F, Schafer E, Harter K.** 2001. Interaction of the response regulator ARR4 with phytochrome B in modulating red light signalling. *Science* **294**, 1108–1111.

**Tajima Y, Imamura A, Kiba T, Amano Y, Yamashino T, Mizuno T.** 2004. Comparative studies on the type-B response regulators revealing their distinctive properties in the His-to-Asp phosphorelay signal transduction of *Arabidopsis thaliana*. *Plant and Cell Physiology* **45**, 28–39.

**To JP, Deruere J, Maxwell BB, Morris VF, Hutchison CE, Ferreira FJ, Schaller GE, Kieber JJ.** 2007. Cytokinin regulates type-A *Arabidopsis* response regulator activity and protein stability via two-component phosphorelay. *The Plant Cell* **19**, 3901–3914.

**To JP, Haberer G, Ferreira FJ, Deruere J, Mason MG, Schaller GE, Alonso JM, Ecker JR, Kieber JJ.** 2004. Type-A *Arabidopsis* response regulators are partially redundant negative regulators of cytokinin signalling. *The Plant Cell* **16**, 658–671.

**To JP, Kieber JJ.** 2008. Cytokinin signalling: two-components and more. *Trends in Plant Science* **13**, 85–92.

**Ueguchi C, Sato S, Kato T, Tabata S.** 2001. The AHK4 gene involved in the cytokinin-signalling pathway as a direct receptor molecule in *Arabidopsis thaliana*. *Plant and Cell Physiology* **42**, 751–755.

**Vision TJ, Brown DG, Tanksley SD.** 2000. The origins of genomic duplications in *Arabidopsis*. *Science* **290**, 2114–2117.

**Werner T, Schmülling T.** 2009. Cytokinin action in plant development. *Current Opinion in Plant Biology* **12**, 527–538.

**West AH, Stock AM.** 2001. Histidine kinases and response regulator proteins in two-component signalling systems. *Trends in Biochemical Sciences* **26**, 369–376.

**Wickson M, Thimann K.** 1958. The antagonism of auxin and kinetin in apical dominance. *Physiologia Plantarum* **11**, 62–74.

**Yamada H, Suzuki T, Terada K, Takei K, Ishikawa K, Miwa K, Yamashino T, Mizuno T.** 2001. The *Arabidopsis* AHK4 histidine kinase is a cytokinin-binding receptor that transduces cytokinin signals across the membrane. *Plant and Cell Physiology* **42**, 1017–1023.

**Yokoyama A, Yamashino T, Amano Y, Tajima Y, Imamura A, Sakakibara H, Mizuno T.** 2007. Type-B ARR transcription factors, ARR10 and ARR12, are implicated in cytokinin-mediated regulation of protoxylem differentiation in roots of *Arabidopsis thaliana*. *Plant and Cell Physiology* **48**, 84–96.

**Yonekura-Sakakibara K, Kojima M, Yamaya T, Sakakibara H.** 2004. Molecular characterization of cytokinin-responsive histidine kinases in maize. Differential ligand preferences and response to cis-zeatin. *Plant Physiology* **134**, 1654–1661.

**Zhao Z, Andersen SU, Ljung K, Dolezal K, Miotk A, Schultheiss SJ, Lohmann JU.** 2010. Hormonal control of the shoot stem-cell niche. *Nature* **465**, 1089–1092.