Cell walls as a stage for intercellular communication regulating shoot meristem development

Toshiaki Tameshige 1, Yuki Hirakawa 1, Keiko U. Torii 1,2,3* and Naoyuki Uchida 1*

1 Institute of Transformative Bio-Molecules (WPI-ITbM), Nagoya University, Nagoya, Japan, 2 Department of Biology, University of Washington, Seattle, WA, USA, 3 Howard Hughes Medical Institute, University of Washington, Seattle, WA, USA

Aboveground organs of plants are ultimately derived/generated from the shoot apical meristem (SAM), which is a proliferative tissue located at the apex of the stem. The SAM contains a population of stem cells that provide new cells for organ/tissue formation. The SAM is composed of distinct cell layers and zones with different properties. Primordia of lateral organs develop at the periphery of the SAM. The shoot apex is a dynamic and complex tissue, and as such intercellular communications among cells, layers and zones play significant roles in the coordination of cell proliferation, growth and differentiation to achieve elaborate morphogenesis. Recent findings have highlighted the importance of a number of signaling molecules acting in the cell wall space for the intercellular communication, including classic phytohormones and secretory peptides. Moreover, accumulating evidence has revealed that cell wall properties and their modifying enzymes modulate hormone actions. In this review, we outline how behaviors of signaling molecules and changes of cell wall properties are integrated for the shoot meristem regulation.

Keywords: auxin, cell wall, cytokinin, intercellular communication, organ primordia, peptide hormone, physical stress, shoot apical meristem

Introduction

Plants elongate stems upward, expand leaves widely to perceive the sunlight, and form flowers for reproduction. These aboveground organs are all developed from the shoot apical meristem (SAM), the proliferative tissue located at the top of the stem. The SAM contains a population of stem cells, which are characterized by two functions: providing new cells for organ/tissue formation and maintaining their own undifferentiated population. In typical eudicots, the SAM is composed of three clonally distinct cell layers, L1, L2, and L3, from outermost to inner cell layers (Steeves and Sussex, 1989; Bowman and Eshed, 2000). Cells in the L1 and L2 layers divide anticlinally, thus serving as the source of epidermal/subepidermal tissues that cover whole aerial parts. On the other hand, cells in the L3 layer divide in various planes to give rise to other inner tissues. The SAM can also be divided into three zones with different anatomical properties: the central zone (CZ) at the top, the peripheral zone (PZ), and the rib zone (RZ) beneath the CZ (Steeves and Sussex, 1989; Bowman and Eshed, 2000). The CZ contains less mitotically active stem cells, replenishing cells for the surrounding PZ and RZ, where cells divide more rapidly and give rise to lateral organs and stems. Primordia of leaves and flowers are formed successively at the periphery of the SAM with a constant divergent angle, resulting in beautifully arranged patterns of the lateral organs (phyllotaxis; Jean, 1994). During organ initiation, cells in a corresponding part of the PZ swell and divide to form a bulge-shaped primordium, and they further proliferate to form a lateral organ.
Intercellular communication plays crucial roles for the coordination among cells and tissues in the shoot apex to achieve elaborate morphogenesis of the plant body. Classically, a series of surgical experiments have predicted the presence of such signals (Steeves and Sussex, 1989). Recent molecular studies have revealed that not only small molecular weight phytohormones but also secretory peptides mediate intercellular signaling. Furthermore, accumulating evidence has highlighted the importance of the extracellular cell wall space for hormone actions. In this review, we outline intercellular communication in the shoot apex, especially focusing on events in the extracellular space, such as hormone transport, metabolism and the dynamics of the cell wall properties.

**Auxin Transport through the Extracellular Space is Regulated by Cell Wall Properties**

Among phytohormones, auxin has been the best characterized in shoot development (Davies, 1995). Auxin regulates a range of developmental processes in specific cells. The following two perception systems for auxin have been reported to mediate the auxin action. Firstly, a group of nuclear-localized receptors encoded by TIR1 (TRANSPORT INHIBITOR RESPONSE 1)/AFB (AUXIN F-BOX) genes perceive auxin. In the presence of auxin, the receptors activate ARF (AUXIN RESPONSE FACTOR) family transcription factors to regulate their target genes (Guilfoyle and Hagen, 2007; Salehin et al., 2015). Secondly, an extracellular receptor, ABP1 (AUXIN BINDING PROTEIN1, binds to auxin (Löbler and Klämbt, 1985). Auxin activates ROP (RHO OF PLANTS) signaling in an ABP1-dependent manner, which in turn regulates clathrin-coated vesicle trafficking and cytoskeleton dynamics (Robert et al., 2010; Xù et al., 2010; Nagawa et al., 2012; Grones and Friml, 2015). In the L1 layer of the SAM, auxin accumulation induces formation of lateral organ primordia. Thus the auxin distribution pattern determines the phyllotaxis. The accumulated auxin in the L1 layer is subsequently transported into underlying L2 and L3 tissues (Benková et al., 2003; Reinhardt et al., 2003; Heisler et al., 2005; Bayer et al., 2009). This auxin flow induces vascular differentiation that eventually connects a vascular network from the primordium to stem vasculatures (Bayer et al., 2009). In a growing primordium, auxin is again accumulated in a dotted pattern in the marginal epidermis, inducing formation of leaflet, lobes, serration and venation (Hay et al., 2006; Scarpella et al., 2006; Barkoulas et al., 2006).

The major natural auxin, indole-3-acetic acid (IAA), is synthesized by intracellular enzymes, which are expressed with specific spatio-temporal patterns (Zhao, 2008; Chandler, 2009). Then, intercellular transport of auxin from the biosynthesis sites determines its distribution pattern. Auxin transport is facilitated by plasma membrane-localized auxin efflux carrier protein, PIN1 (PIN-FORMED 1). Genetic and chemical perturbation of PIN1 impairs the local auxin accumulation and following developmental events: lateral organ initiation (Okada et al., 1991; Reinhardt et al., 2000), phyllotaxis (Guenot et al., 2012), vascular patterning (Scarpella et al., 2006), and leaf margin morphogenesis (Hay et al., 2006). In these events, PIN1 proteins localize at a specific part of the plasma membrane and the coherent PIN1 polarization in a group of cells causes directional auxin flow toward the point of its accumulation (Bouillé et al., 2007; Nakamura et al., 2012; Luschnig and Vert, 2014). Studies on mechanisms for the PIN1 polarization proposed that PIN1 proteins preferentially localize toward the most auxin-rich neighboring cell or toward the cell wall where the auxin flux is the highest (Jönsson et al., 2006; Smith et al., 2006; Stoma et al., 2008; Bayer et al., 2009). It was also proposed that PIN1 proteins concentrate toward the cell wall that exhibits the highest stress (Heisler et al., 2010; Nakayama et al., 2012; Braybrook and Peaucelle, 2013). These two types of models have started to be integrated by recent studies and the details of this integration will be described in the later section of this review on physical properties of the cell walls. These findings highlight a novel role for cell walls in the regulation of auxin distribution. It has been discussed that, in the SAM and leaf primordia, PIN1 dynamics might be differently regulated between the epidermal L1 layer and the inner L2/L3 tissues (Tsugekí et al., 2009; O’Connor et al., 2014). Because the proposed models for stress responses only dealt with phenomenon in the L1 layer, it would be important to investigate whether these models can be applied to the L2/L3 tissues.

The auxin distribution pattern also depends on its influx into cells since mutations in auxin influx carrier genes lead to abnormal phyllotaxis (Cheng et al., 2007; Bainbridge et al., 2008). Interestingly, the auxin influx rate is affected by a chemical property of cell wall space. Major auxin influx carriers, AUX1/LAX (LIKE-AUX1) proteins, catalyze H+/IAA-symport (Yang et al., 2006; Bouillé et al., 2007; Vieten et al., 2007). Therefore, this process largely depends on the pH difference across the plasma membrane. In addition, the auxin influx occurs by diffusion. Because the extracellular pH is acidic (~5.5) and the cytosolic pH is neutral (~7.0), a substantial amount of IAA is protonated in the extracellular space and is ionized in the cytosol. As only the protonated form is freely transported through lipophilic plasma membranes because of its neutral charge, the diffusion is unidirectional from outside of the cell to the inside. Plants indeed alter the extracellular pH to create the auxin gradient in hypocotyls by utilizing plasma membrane-localized H⁺-ATPases (Hohm et al., 2014).

**Cytokinin also Acts for Intercellular Communication**

Cytokinins (CKs) are adenine derivatives, which also act as a phytohormone playing significant roles in the SAM activity and organ morphogenesis. Indeed, two key transcription factors for the SAM regulation, SHOOT MERISTEMLESS (STM) and WUSCHEL (WUS), control the CK homeostasis and signaling, highlighting the importance of CK for the regulation (Yanai et al., 2005; Gordon et al., 2009). CK also impacts phyllotaxis (Giuilini et al., 2004), lateral organ initiation (Yoshida et al., 2011), leaf margin morphogenesis (Greenboim-Wainberg et al., 2005; Shani et al., 2010; Efroni et al., 2013), and leaf vein patterning (Werner et al., 2003).

Cytokinins is transported not only locally among neighboring cells but also distantly between shoot and root. CK moves from shoot to root symplastically via phloem and from root to shoot apoplastically via xylem (Kudo et al., 2010). The intercellular CK movement is facilitated by both transporters and passive diffusion.
ENT (EQUILIBRATIVE NUCLEOSIDE TRANSPORTER) and PUP (PURINE PERMEASE) proteins act as importers (Bürkle et al., 2003; Li et al., 2003; Hirose et al., 2005; Sun et al., 2005; Cedzich et al., 2008; Qi and Xiong, 2013). On the other hand, ABCG14 (ATP-BINDING CASSETTE TRANSPORTER SUB- FAMILY G14) was implicated as an exporter candidate. Some of ENTs and PUPs are expressed in shoot tissues and their mutations change shoot morphologies. However, a large and complex redundancy among these family members hampers comprehensive analysis to further investigate roles for these transporters. The ABCG14 loss-of-function mutation alters the SAM size and growth rate. Interestingly, grafting experiments indicate that the ABCG14 expression in root is essential for shoot development (Ko et al., 2014), demonstrating the significance of the CK translocation between shoot and root for the shoot development. On the other hand, the importance of the CK transporters for the local movement is still unclear. At least, in contrast to auxin transport, highly directional transport is not assumed and simple diffusion of CK is predicted owing to its high membrane permeability (Laloue et al., 1991; Kudoyarova et al., 2014). Accordingly, recent mathematical models have reconstituted expression patterns of CK-responsive genes for the SAM regulation and vascular formation by assuming only simple and constant diffusion for the CK transport (Chickarmane et al., 2012; De Rybel et al., 2014).

Enzymes responsible for CK biosynthesis are localized in cytosol and intracellular organelles (Kieber and Schaller, 2014), while the degradation is catalyzed by CKX (CYTOKININ DEHYDROGENASE) family members, some of which are reported to act as extracellular proteins (Motyka et al., 2003; Werner et al., 2003; Kieber and Schaller, 2014). In addition, CKX members show different substrate preferences and expression patterns (Werner et al., 2003; Gajdošová et al., 2011; Köllmer et al., 2014). These imply that each CKX degrades a specific pool of CK according to their particular spatial distribution and substrate preference. While it was shown that the mutant of a putative extracellular CKX, CKX5, displays defects of the SAM and stem morphologies (Bartrina et al., 2011), the biological significance of the extracellular CK degradation is still largely obscure. It was reported that, in moss, the extracellular amount of CK correlates with some CK-responsive genes for the SAM regulation and vascular formations change shoot morphologies. However, a large and complex systemin was shown to localize in the cytosol (Narváez-Vásquez and Ryan, 2004), most of the others are presumed to be secreted into the apoplasts by the N-terminal signal peptide (Matsubayashi, 2014). These secreted peptides bind to specific cell-surface-localized receptors at target cells and affect cellular behaviors such as cell division, cell morphogenesis and cell fate determination. Peptide hormone genes are classified into distinct families based on the similarity in their mature peptide sequences. Each family contains multiple genes, which produce structurally similar or even identical mature peptides. Post-translational modification is also critical for their bioactivities. Secreted peptides often contain proline, tyrosine and/or cysteine residues post-translationally modified by specific enzymes (Komori et al., 2009; Ogawa-Ohnishi et al., 2013; Matsubayashi, 2014). Also, some proteases are responsible for the proteolytic cleavage in the maturation steps (Berger and Altmann, 2008; Matsubayashi et al., 2014). In the SAM, CLAVATA3 (CLV3) peptide, a member of CLE (CLV3/ESR-related) peptide family, mediates intercellular communications maintaining stem cell homeostasis (Cock and McCormick, 2001). The structure of the mature CLV3 peptide was determined as a 13 amino-acid peptide containing two hydroxyproline residues, one of which was further triarabinosylated (Ohyama et al., 2009). The CLV3 peptide is produced by stem cells in the CZ and perceived by its receptors at neighboring cells (Fletcher et al., 1999; Brand et al., 2000; Schoof et al., 2000). Leucine-rich repeat (LRR)-type receptors participate in the CLV3 signaling pathway. CLV1 is an LRR receptor kinase (LRR-RK), which binds to CLV3 (Ogawa et al., 2008; Ohyama et al., 2009). The BAM (BARELY ANY MEISTEM) proteins are close relatives of CLV1. Genetic and biochemical studies implied that BAMs also possess the binding capability to CLV3 peptides (DeYoung et al., 2006; DeYoung and Clark, 2008; Shinohara et al., 2012). In addition, other membrane-localized proteins including CLV2,
CRN (CORYNE)/SOL2 (SUPPRESSOR OF LLP1 2) and RPK2 (RECEPTOR-LIKE PROTEIN KINASE 2) are involved in the CLV3 pathway (Miwa et al., 2008; Müller et al., 2008; Kinoshita et al., 2010). These proteins form various combinations of receptor complexes to mediate CLV3 signaling (Bleckmann et al., 2010; Guo et al., 2010; Kinoshita et al., 2010; Zhu et al., 2010). The CLV3 signal represses the expression of WUS that encodes a transcription factor promoting the proliferation of CLV3-producing stem cells (Mayer et al., 1998; Brand et al., 2000; Schoof et al., 2000). This local feedback is integrated with CK and auxin signaling, thus maintaining the dynamic SAM architecture (Leibfried et al., 2005; Gordon et al., 2009; Zhao et al., 2010; Chickarmane et al., 2012).

Phytosulfokine (PSK) is a disulfated five amino-acid peptide identified first in the Asparagus cell culture as a factor that promotes cell proliferation (Matsubayashi and Sakagami, 1996). Five genes produce the identical PSK peptides in Arabidopsis and are expressed in almost all tissues (Matsubayashi et al., 2006). PLANT PEPTIDE CONTAINING SULFATED TYROSIINE 1 (PSY1), 18 amino acid glycopeptide, displays a biological activity similar to PSK (Amano et al., 2007). A PSK receptor (PSKR) was biochemically identified from carrot Daucus carota microsomal fractions (Matsubayashi et al., 2002). Arabidopsis homologs of DcPSKR act as receptors for PSK or PSY1, being expressed in a broad range of tissues including the SAM (Matsubayashi et al., 2006; Amano et al., 2007). Genetic studies of the receptors highlight the importance of PSK/PSY1 signaling in the cell proliferation, expansion and wound repair (Matsubayashi et al., 2006; Amano et al., 2007).

ERECTA (ER)-family LRR-RKs regulate various aspects of growth and development such as stem growth, stomatal patterning and the SAM regulation (Tori et al., 1996; Shpak et al., 2004; Uchida et al., 2011, 2013; Chen et al., 2013). The loss of the entire family activities impairs the SAM homeostasis, leading to an increase in stem cell population (Uchida et al., 2013). Because the SAM of er-family mutant shows enhanced CK response and abnormal auxin accumulation pattern (Chen et al., 2013; Uchida et al., 2013), ER-family signaling is thought to have crosstalks with CK and auxin pathways. Although a ligand for the ER family in the SAM regulation is still unknown, the ligands for stem growth and stomatal development have been identified: All of them belong to the same family of peptide hormones, the EPF (EPIDERMAL PATTERNING FACTOR)/EPFL (EPF-LIKE) family (Hara et al., 2007, 2009; Hunt and Gray, 2009; Abrash and Bergmann, 2010; Hunt et al., 2010; Kondo et al., 2010; Sugano et al., 2010; Abrash et al., 2011; Uchida et al., 2012, 2013). The EPF/EPFL family encodes cysteine-rich secretory peptides, which possess intramolecular disulfide bonds essential for the conformation of their bioactive mature forms (Kondo et al., 2010; Sugano et al., 2010; Ohki et al., 2011). A yet unknown ligand for ER family for the SAM regulation may also be a member of this family.

To date, more than 15 peptide hormone families have been described (Kondo et al., 2014). Though each family consists of multiple paralogs, roles for most of them are still obscure. Also, it is expected that yet unidentified peptide hormone genes can be found in genomes. It would be an important challenge to identify further secretory peptides, which participate in the shoot apex regulation.

**Cell Wall Loosening Proteins as Key Factors in Organ Formation**

Plant cells need to extend their cell walls during growth and development. Cell wall extensibility is enhanced by growth promoting phytohormones, including auxin and CK (Cleland, 1958; Thomas et al., 1981), and has started to be recognized as a key factor that determines developmental patterns and cell fates. The first breakthrough came from experiments using an apoplastic protein, EXP (EXPANSIN; Fleming et al., 1997; Pien et al., 2001), which relaxes cellulose microfibril network by binding to xyloglucan (Wang et al., 2013). The EXP expression increases in newly formed leaf primordia. Because its wall-loosening activity exhibits an acidic pH optimum, it is suggested that auxin accumulation in leaf primordia further increases the EXP activity (McQueen-Mason and Cosgrove, 1994; Cleland, 2001). It was also reported that local application of exogenous EXP proteins as well as artificial expression of EXP induces leaf formation on the SAM (Fleming et al., 1997). These indicate that local loosening of the cell wall triggers organ initiation. Auxin is also known to promote demethylsterification of pectin (Bryan and Newcomb, 1954; Braybrook and Peaucelle, 2013), and another secreted enzyme, PME (PECTIN METHYLESTERASE), was shown to loosen cell walls by demethylsterifying pectin (Peaucelle et al., 2008, 2011a). PME induces the organ initiation when applied to the SAM surface as well as EXP (Peaucelle et al., 2008, 2011a). Furthermore, a member of PGX (POLYGALACTURONASE) family regulates the organ initiation pattern by cleaving pectins (Xiao et al., 2014). These findings highlight the significance of the dynamic nature of cell wall extensibility during organ development.

The importance of the cell wall loosening has also been characterized in the stem cell regulation in moss. During stem cell induction triggered by leaf excision in Physcomitrella, some cell wall loosening enzymes are up-regulated (Sakakibara et al., 2014). Meanwhile, transient expression of EXP enhances the stem cell formation (Sakakibara et al., 2014). While the underlying molecular mechanisms may not be conserved between the SAM of vascular plants and stem cells of mosses, these observations emphasize the importance of cell wall extensibility in cell fate determination.

**Cell Wall Loosening Changes Microtubule Orientation and Auxin Pattern in the SAM**

Cell wall extensibility is a physical property. Therefore, it has been a key question how such a physical property is decoded as a developmental signal to change cellular behaviors. The physical force generated by cell wall loosening could provide an answer. In a growing tissue, cells are constrained by the cell wall. Therefore, cell wall loosening results in cell swelling and pushing the neighboring cells. Recent studies revealed that such pushing force regulates cellular behaviors by affecting the following two factors: cortical microtubule (CMT) orientation and PIN1 protein localization (Figure 1).

The first player, CMT, is a type of cytoskeleton microtubules located under the plasma membrane. In general, the CMT orientation correlates with the stress direction in various plant tissues (Green and King, 1966; Williamson, 1990; Cleary and Hardham,
local stress in the neighboring cells, and it has been proposed that the PIN1 protein is preferentially localized to a part of plasma membrane where the contacting cell wall is the most stressed (Heisler et al., 2010; Figure 1B). A plausible model for this characteristic localization is as follows. PIN1 distribution is dynamically regulated through exocytosis and endocytosis, which increase and decrease the local PIN1 amount in the plasma membrane, respectively. Exocytosis is activated near the highly stressed portion of cell walls where the tension of plasma membrane is also high, thus leading to PIN1 enrichment there (Nakayama et al., 2012; Figure 1B). The resulting PIN1 localization facilitates transport of auxin into the wall-loosening cell (Figures 1B,C, right). Thus, PIN1 mediates this positive feedback to enhance both cell wall loosening and local auxin accumulation (Braybrook and Peaucelle, 2013; Figures 1B,C, right).

Taken together, cell wall loosening triggers organ formation by the following two feedback mechanism (Sampathkumar et al., 2014). One is the feedback between the CMT anisotropy and the SAM geometry (Figures 1A,C left). The other is between PIN1-dependent auxin transport and auxin-induced wall loosening (Figures 1B,C right). Because the auxin accumulation increases the CMT anisotropy (Sassi et al., 2014), these two feedback circuits are interconnected (Figure 1C). Therefore, any of auxin accumulation, cell wall loosening and CMT anisotropy change can initiate organ primordium formation. It would be interesting to investigate which of them is the earliest event in nature.

In addition, it was recently reported that a membrane-bound kinase, D6PK (D6 PROTEIN KINASE), phosphorylates PIN1 to control its localization and, vice versa, auxin promotes the polar distribution of D6PK at the plasma membrane, suggesting another feedback mechanism for the auxin-PIN1 mutual regulation (Zourelidou et al., 2009; Willige et al., 2013; Barbosa et al., 2014; Figure 1C). It would be interesting to investigate whether and/or how this D6PK-dependent mechanism and the above-mentioned stress-mediated mechanisms are integrated.

Remaining Questions on Relationships between Cell Wall Loosening and Organ Development

Whereas roles for cell wall loosening proteins in organ formation are evident and the underlying mechanisms have begun to unveil, questions and problems to be challenged still remain. Firstly, methods to directly measure physical stress in the SAM and initiating organs need to be further developed, as our current knowledge on the stress has been all indirectly estimated from measurements of other physical properties: the tissue geometry by scanning electron microscopy (Hamant et al., 2008), the elasticity by atomic force microscopy (Peaucelle et al., 2011a) and the cellular volume expansion caused by manipulation of osmotic pressure (Kierzkowski et al., 2012). Therefore, direct measurements of the stress are ultimately required for comprehensive understanding. Developing new applications of micro-manipulation tools

![Figure 1](https://example.com/figure1.png)

**Figure 1** Current model for organ initiation and the role for cell wall loosening. (A,B) The stress from the cell with loosened cell wall leads to reorientation of cortical microtubule (CMT) (A) and PIN1 polarization toward the loosened wall (B) in neighboring cells. (C) Regulatory network among cell wall loosening, CMT and PIN1. Details are mentioned in the text.
YUCCA proteins (e.g., microfluidic device, optical tweezers and magnetic nanoparticles) might help to overcome this issue.

Secondly, little is known about mechanisms by which cells directly perceive the physical stress in the SAM. It has been reported that, in other parts such as roots and pollen tubes, loss of function of some receptor-like proteins (THESEUS1, FERONIA, ANXUR1/2, and Receptor-like protein 44) and putative mechanosensitive channels (MCA1/2) alters cellular responses to physical stress or changes in cell wall polysaccharide composition (Hématy et al., 2007; Nakagawa et al., 2007; Boisson-Dernier et al., 2013; Shih et al., 2014; Wolf et al., 2014). Though these proteins could be candidates for sensors to monitor physical stress or cell wall conditions (Cheung and Wu, 2011; Höfte, 2015), direct evidence is still lacking. It also remains to examine whether these proteins contribute to the shoot apex regulation.

Thirdly, though the pin1 mutation and the treatment of auxin transport inhibitors impair leaf morphogenesis and phyllotaxis (Kawamura et al., 2010; Guenot et al., 2012), they do not block the leaf initiation itself. Therefore, the PIN1-independent organ initiation machinery must exist. Some studies implicated that the leaf initiation itself. Therefore, the PIN1-independent organ initiation machinery must exist. Some studies implicated that the leaf initiation itself. Therefore, the PIN1-independent organ initiation machinery must exist. Some studies implicated that the leaf initiation itself. Therefore, the PIN1-independent organ initiation machinery must exist. Some studies implicated that the leaf initiation itself. Therefore, the PIN1-independent organ initiation machinery must exist. Some studies implicated that the leaf initiation itself. Therefore, the PIN1-independent organ initiation machinery must exist. Some studies implicated that the leaf initiation itself. Therefore, the PIN1-independent organ initiation machinery must exist.

Lastly, compared with the SAM regulation, there is only limited information as to whether and/or how cell wall loosening is regulated in growth and morphogenesis of other tissues. Some studies have shown that EXP induces the leaf lobe formation and increases the total leaf size (Pien et al., 2001; Sloan et al., 2009; Goh et al., 2012) and also that PME promotes stem elongation (Peaucelle et al., 2011b). However, the involvement of auxin and CMT is unclear in these processes. To further understand the developmental roles for the cell wall loosening, it is important to characterize similarities and differences of molecular mechanisms in different developmental events.

**Concluding Remarks**

In this review, we outlined current knowledge on the regulation of shoot apex development, especially highlighting signaling molecules, physicochemical properties of cell walls and their modifiers in the extracellular space. A great variety of their actions and interactions demonstrate the importance of the cell wall space as a field for intercellular communication more than just a wall that separates individual cells. This viewpoint is indispensable to understand how plants have evolved their own multicellular body whose cells are interconnected by cell walls in sharp contrast to the animal body. Further technical developments in imaging, measurement, manipulation and mathematical modeling will provide more insights into the dynamics and functions of the cell wall space.

**Acknowledgments**

This paper was supported by MEXT/JSPS KAKENHI Grant Numbers 14018452 to YH, 26291057 and 26113507 to KT, and also 24570050, 25114511 and 26113707 to NU. NU was also supported by the Toyoaki Foundation. YH is a JSPS research fellow. KT is an investigator of the Howard Hughes Medical Institute and Gordon and Betty Moore Foundation.

**References**

Abrash, E. B., and Bergmann, D. C. (2010). Regional specification of stomatal production by the putative ligand CHALLAH. Development 137, 447–455. doi: 10.1242/dev.040931

Abrash, E. B., Davies, K. A., and Bergmann, D. C. (2011). Generation of signaling specificity in Arabidopsis by spatially restricted buffering of ligand-receptor interactions. Plant Cell 23, 2864–2879. doi: 10.1105/tpc.111.088637

Amano, Y., Tsibouchi, H., Shinohara, H., Ogawa, M., and Matsubayashi, Y. (2007). Tyrosine-sulfated glycopeptide involved in cellular proliferation and expansion in Arabidopsis. Proc. Natl. Acad. Sci. U.S.A. 104, 18333–18338. doi: 10.1073/pnas.0706403104

Bainbridge, K., Guyomar-Ch’s, S., Bayer, E., Swarup, R., Bennett, M., Mandel, T., et al. (2008). Auxin influx carriers stabilize phyllotactic patterning. Genes Dev. 22, 810–823. doi: 10.1101/gad.462608

Barbosa, I. C., Zourelidou, M., Willige, B. C., Weller, B., and Schwechheimer, C. (2014). D6 PROTEIN KINASE activates auxin transport-dependent growth and PIN-FORMED phosphorylation at the plasma membrane. Dev. Cell 29, 674–685. doi: 10.1016/j.devcel.2014.05.006

Barkoulas, M., Hay, A., Kougioumoutzi, E., and Tsiantis, M. (2008). A developmental framework for dissected leaf formation in the Arabidopsis relative Cardamine hirsuta. Nat. Genet. 40, 1136–1141. doi: 10.1038/ng.189

Bartrina, I., Otto, E., Strnad, M., Werner, T., and Schmülling, T. (2011). Cytokinin regulates the activity of reproductive meristems, flower organ size, ovule formation, and thus seed yield in Arabidopsis thaliana. Plant Cell 23, 69–80. doi: 10.1105/tpc.110.079079

Bayer, E. M., Smith, R. S., Mandel, T., Nakayama, N., Sauer, M., Prusinkiewicz, P., et al. (2009). Integration of transport-based models for phyllotaxis and midvein formation. Genes Dev. 23, 373–384. doi: 10.1101/gad.49709

Benková, E., Michniewicz, M., Sauer, M., Teichmann, T., Seijfertová, D., Jürgens, G., et al. (2003). Local, efflux-dependent auxin gradients as a common module for plant organ formation. Cell 115, 591–602. doi: 10.1016/S0092-8674(03)00924-3

Berger, D., and Altmann, T. (2000). A subtilisin-like serine protease involved in the regulation of stomatal density and distribution in Arabidopsis thaliana. Genes Dev. 14, 1119–1131. doi: 10.1101/gad.14.9.1119

Besnard, F., Refai, Y., Morin, V., Marteaux, B., Brunoud, G., Cambier, P., et al. (2014). Cytokinin signalling inhibitory fields provide robustness to phyllotaxis. Nature 505, 417–421. doi: 10.1038/nature12791

Bishopp, A., Help, H., El-Showk, S., Weijers, D., Scheres, B., Friml, J., et al. (2011). A mutually inhibitory interaction between auxin and cytokinin specifies vascular pattern in roots. Curr. Biol. 21, 917–926. doi: 10.1016/j.cub.2011.04.017

Bleckmann, A., Weidtkamp-Peters, S., Seidel, C. A., and Simon, R. (2010). Stem cell signaling in Arabidopsis requires CRN to localize CLV2 to the plasma membrane. Plant Physiol. 152, 166–176. doi: 10.1104/pp.110.149930

Boisson-Dernier, A., Lituiev, D. S., Nestorova, A., Franck, C. M., Thirugnanarajah, S., and Grossniklaus, U. (2013). ANXUR receptor-like kinases coordinate cell wall integrity with growth at the pollen tube tip via NADPH oxidases. PLoS Biol. 11:e1001719. doi: 10.1371/journal.pbio.1001719
cells to the inhibition of cytokinin synthesis. *Carr. Biol.* 17, 922–931. doi: 10.1016/j.cub.2007.05.018

Hirose, N., Makita, N., Yamaya, T., and Sakakibara, H. (2005). Functional characterization and expression analysis of a gene, OsENT2, encoding an equilibrative nucleoside transporter in rice suggest a function in cytokinin transport. *Plant Physiol.* 138, 196–206. doi: 10.1104/pp.105.060137

Höfte, H. (2015). The Yin and Yang of cell wall integrity control: brassinosteroid and FERONIA signaling. *Plant Cell Physiol.* 56, 224–231. doi: 10.1093/pcp/pcu182

Hohm, T., Demarsy, E., Quan, C., Allenbach Petrolati, L., Preuten, T., Vernoux, T., et al. (2014). Plasma membrane H+–ATPase regulation is required for auxin gradient formation preceding phototropic growth. *Mol. Biol. System.* 10, 751. doi: 10.15252/msb.20145247

Hunt, L., Bailey, K. J., and Gray, J. E. (2010). The signalling peptide EPEL9 is a positive regulator of stomatal development. *New Phytol.* 186, 609–614. doi: 10.1111/j.1469-8137.2010.03200.x

Hunt, L., and Gray, J. E. (2009). The signalling peptide EPEF2 controls asymmetric cell division during stomatal development. *Carr. Biol.* 19, 864–869. doi: 10.1016/j.cub.2009.03.069

Jean, R. V. (1994). *Phyllotaxis: A Systemic Study in Plant Morphogenesis*. New York: Cambridge University Press. doi: 10.1017/CBO9780511666933

Jonsson, H., Heisler, M. G., Shapiro, B. E., Meyerowitz, E. M., and Mjolsness, E. (2006). An auxin-driven polarized transport model for phyllotaxis. *Proc. Natl. Acad. Sci. U.S.A.* 103, 16313–16318. doi: 10.1073/pnas.0509391103

Kawamura, E., Horiguchi, G., and Tsukaya, H. (2010). Mechanisms of leaf tooth formation in Arabidopsis. *Plant J.* 62, 429–441. doi: 10.1111/j.1365-313X.2010.04156.x

Kieber, J. J., and Schaller, G. E. (2014). Cytokinins. *Arabidopsis Book* 12:e0168. doi: 10.1199/tab.0168

Kierzkowski, D., Nakayama, N., Routier-Kierzkowska, A. L., Weber, A., Bayer, E., Kieber, J. J., and Schaller, G. E. (2014). Cytokinins control polarity of PIN1-dependent auxin transport during lateral root organogenesis. *Carr. Biol.* 24, 1031–1037. doi: 10.1016/j.cub.2014.04.002

Matsubayashi, Y. (2014). Posttranslationally modified small-peptide signals in plants. *Annu. Rev. Plant Biol.* 65, 385–413. doi: 10.1146/annurev-arplant-053012-120112

Matsubayashi, Y., Ogawa, M., Kihara, H., Niwa, M., and Sakagami, Y. (2006). Disruption and overexpression of *Arabidopsis* phytosulfokine receptor gene affects cellular longevity and potential for growth. *Plant Physiol.* 142, 45–53. doi: 10.1104/pp.106.081109

Matsubayashi, Y., Ogawa, M., Morita, A., and Sakagami, Y. (2002). An LRR receptor kinase involved in perception of a peptide plant hormone, phytosulfokine. *Science* 296, 1470–1472. doi: 10.1126/science.1069607

Matsubayashi, Y., and Sakagami, Y. (1996). Phytosulfokine, sulfated peptides that induce proliferation of single mesophyll cells of *Asparagus officinalis*. In *Proc. Natl. Acad. Sci. U.S.A.* 93, 7623–7627.

Mayer, K. F., Schoof, H., Haecker, A., Lenhard, M., Jürgens, G., and Laux, T. (1998). Role of WUSCHEL in regulating stem cell fate in the *Arabidopsis* shoot meristem. *Cell* 95, 805–815. doi: 10.1016/S0092-8674(00)81703-1

McQueen-Mason, S., and Conejero, D. J. (1994). Disruption of hydrogen bonding between plant cell wall polymers by proteins that induce wall extension. *Proc. Natl. Acad. Sci. U.S.A.* 91, 6574–6578.

Miwa, H., Betsuyaku, S., Iwamoto, K., Kinoshita, A., Fukuda, H., and Sawa, S. (2008). The receptor-like kinase SOL2 mediates CLE signaling in *Arabidopsis*. *Plant Cell Physiol.* 49, 1752–1757. doi: 10.1093/pcp/pcn148

Motyka, V., Vaňková, R., Čapková, V., Petrášek, J., Kamínek, M., and Schmülling, T. (2003). Cytokinin-induced upregulation of cytokinin oxidase activity in tobacco includes changes in enzyme glycosylation and secretion. *Physiol. Plant.* 117, 11–21. doi: 10.1046/j.1399-3054.2003.1107102.x

Müller, R., Bleckmann, A., and Simon, R. (2008). The receptor kinase CORYNE of *Arabidopsis* transmits the stem cell-limiting signal *CLAVATA3* independently of *CLAVATA1*. *Plant Cell* 20, 934–946. doi: 10.1093/pcp/pcn148

Murray, J. A., Jones, A., Godin, C., and Traas, J. (2012). Systems analysis of shoot apical meristem growth and development: integrating hormonal and mechanical signaling. *Plant Cell* 24, 3907–3919. doi: 10.1016/j.tplastd.2012.010194

Nagawa, S., Xu, T., Lin, D., Dhouktshe, P., Zhang, X., Friml, J., et al. (2012). ROP GTase-dependent actin microfilaments promote PIN1 polarization by localized inhibition of clathrin-dependent endocytosis. *PLoS Biol.* 10:e1001299. doi: 10.1371/journal.pbio.1001299

Nakagawa, Y., Katagiri, T., Shinozaki, K., Qi, Z., Tatsumi, H., Fujuchi, T., et al. (2007). *Arabidopsis* plasma membrane protein crucial for Ca2+ influx and touch sensing in roots. *Proc. Natl. Acad. Sci. U.S.A.* 104, 3639–3644. doi: 10.1073/pnas.0607703104

Nakamura, M., Kiefer, C. S., and Grebe, M. (2012). Planar polarity, tissue polarity and planar morphogenesis in plants. *Curr. Opin. Plant Biol.* 15, 593–600. doi: 10.1016/j.pbi.2012.07.006

Nakayama, N., Smith, R. S., Mandel, T., Robinson, S., Kimura, S., Boudaoud, A., et al. (2012). Mechanical regulation of auxin-mediated growth. *Curr. Biol.* 22, 1468–1476. doi: 10.1016/j.cub.2012.06.050

Narvaez-Vásquez, I., and Ryan, C. A. (2004). The cellular localization of pro symplasmic: a functional role for plasmemembrane in systemic wound signaling. *Planta* 218, 360–369. doi: 10.1007/s00425-003-1115-3

O’Connor, D. L., Runions, A., Sluis, A., Bragg, J., Vogel, J. P., Prusinkiewicz, P., et al. (2014). A division in PIN-mediated auxin patterning during organ initiation in grasses. *PLoS Comput. Biol.* 10:e1003447. doi: 10.1371/journal.pcbi.1003447
Ogawa-Oshinshi, M., Matsuhashi, W., and Matsubayashi, Y. (2013). Identification of three hydroxyproline O-arabinosyltransferases in Arabidopsis thaliana. Nat. Chem. Biol. 9, 726–730. doi: 10.1038/nchembio.1351

Ogawa, M., Shinozaka, H., Sakagami, Y., and Matsubayashi, Y. (2008). Arabidopsis CLV3 peptide directly binds CLV1 ectodomain. Science 319, 294. doi: 10.1126/science.1150083

Ohk, S., Takeuchi, M., and Mori, M. (2011). The NMR structure of stomagen reveals the basis of stomatal density regulation by plant peptide hormones. Nat. Commun. 2, 512. doi: 10.1038/ncomms1520

Ohyama, K., Shinozaka, H., Ogawa-Oshinshi, M., and Matsubayashi, Y. (2009). A glycopeptide regulating stem cell fate in Arabidopsis thaliana. Nat. Chem. Biol. 5, 578–580. doi: 10.1038/nchembio.182

Okada, K., Ueda, J., Komaki, M. K., Bell, C. J., and Shimura, Y. (1991). Requirement of auxin for shoot meristem development in Arabidopsis thaliana. Plant Cell 3, 677–684. doi: 10.1105/tpc.3.7.677

Paredes, A. R., Somerville, C. R., and Ehrhardt, D. W. (2006). Visualization of cel lulose synthase demonstrates functional association with microtubules. Science 312, 1491–1495. doi: 10.1126/science.1126551

Pearce, G., Strydom, D., Johnson, S., and Ryan, C. A. (1991). A polypeptide from tomato leaves induces wound-inducible proteinase inhibitor proteins. Science 235, 895–897. doi: 10.1126/science.235.5202.895

Peaucelle, A., Braybrook, S. A., Le Guillou, L., Bron, E., Kuhlemeier, C., and Hönke, H. (2011a). Pectin-induced changes in cell wall mechanics underlie organ initiation in Arabidopsis. Curr. Biol. 21, 1720–1726. doi: 10.1016/j.cub.2011.08.057

Peaucelle, A., Louvet, R., Johansen, J. N., Salsac, F., Morin, H., Fournet, F., et al. (2011b). The transcription factor BELLRINGER modulates phyllotaxis by regulating the expression of a pectin methylesterase in Arabidopsis. Development 138, 4733–4741. doi: 10.1242/dev.072496

Peaucelle, A., Louvet, R., Johansen, J. N., Hönke, H., Laufs, P., Pelloux, J., et al. (2008). Arabidopsis phyllotaxis is controlled by the methyl-esterification status of cell-wall pectins. Curr. Biol. 18, 1943–1948. doi: 10.1016/j.cub.2008.10.065

Pien, S., Wyrzykowska, J., McQueen-Mason, S., Smart, C., and Fleming, A. (2001). Local expression of expansin induces the entire process of leaf development and modifies leaf shape. Proc. Natl. Acad. Sci. U.S.A. 98, 11812–11817. doi: 10.1073/pnas.191380498

Qi, Z., and Xiong, L. (2013). Characterization of a purine permease family gene OsPUP7 involved in growth and development control in rice. J. Integr. Plant Biol. 55, 1119–1135. doi: 10.1111/jipb.12101

Reinhardt, D., Mandel, T., and Kuhlemeier, C. (2000). Auxin regulates the initiation and radial position of plant lateral organs. Plant Cell 12, 507–518. doi: 10.1105/tpc.12.4.507

Reinhardt, D., Pesce, R. E., Stieger, P., Mandel, T., Baltensperger, K., Bennett, M., et al. (2003). Regulation of phyllotaxis by polar auxin transport. Nature 426, 255–260. doi: 10.1038/nature02081

Robert, S., Kleine-Vehn, J., Barbez, E., Sauer, M., Picoret, T., Baster, P., et al. (2010). ABP1 mediates auxin inhibition of clathrin-dependent endocytosis in Arabidopsis. Cell 143, 111–121. doi: 10.1016/j.cell.2010.09.027

Sakakibara, K., Reisewitz, P., Aoyama, T., Friedrich, T., Ando, S., Sato, Y., et al. (2013). SUPPRESSOR OF LLP1-mediated C-terminal processing is required for integration of Arabidopsis SAM1 reveals diverse lipid recognition mechanisms of plant LRR-RKs. Plant J. 70, 845–854. doi: 10.1111/j.1365-312X.2012.04934.x

Shpak, E. D., Berthiaume, C. T., Hill, E. J., and Torii, K. U. (2004). Synergistic interaction of three ERECTA-family receptor-like kinases controls Arabidopsis organ growth and flower development by promoting cell proliferation. Development 131, 1491–1501. doi: 10.1242/dev.01028

Sloan, J., Backhaus, A., Malinowski, R., McQueen-Mason, S., and Fleming, A. J. (2009). Positioned control of expansin activity during leaf development identifies a sensitivity window for expansin-mediated induction of leaf growth. Plant Physiol. 150, 1484–1495. doi: 10.1104/pp.109.144683

Smith, R. S., Guyomarch, S., Mandel, T., Reinhardt, D., Kuhlemeier, C., and Prusinkiewicz, P. (2006). A plausible model of phyllotaxis. Proc. Natl. Acad. Sci. U.S.A. 103, 1301–1306. doi: 10.1073/pnas.0510457103

Srivastava, R., Liu, J. X., and Howell, S. H. (2008). Proteolytic processing of a precursor protein for a growth-promoting peptide by a subtilisin serine protease in Arabidopsis. Plant J. 56, 219–227. doi: 10.1111/j.1365-313X.2008.05398.x

Steeves, T. A., and Sussex, I. M. (1989). Patterns in Plant Development, 2nd Edn. New York: Cambridge University Press. doi: 10.1017/CBO9781107666657

Sugano, S. S., Shimada, T., Imai, Y., Okawa, K., Tamai, A., Mori, M., et al. (2010). Stomagen positively regulates stomatal density in Arabidopsis. Nature 463, 241–244. doi: 10.1038/nature08682

Sun, J., Qiao, H., Wang, X. C., Wen, P., Xue, L., Sakakibara, H., et al. (2005). The Arabidopsis SOI33/AtENT8 gene encodes a putative equilibrative nucleoside transporter that is involved in cytokinin transport in Planta. J. Integr. Plant Biol. 47, 588–603. doi: 10.1111/j.1744-7909.2005.00104.x

Tamaki, T., Betsuyaku, S., Fujiiwa, M., Fukao, Y., Fukuda, H., and Sawa, S. (2013). SUPPRESSOR OF LPL1 is a 1-mediated C-terminal processing is critical for CLE19 peptide activity. Plant J. 76, 970–981. doi: 10.1111/jtp.12349

Thomas, J., Ross, C. W., Chastain, C. J., Koomanoff, N., and Hendrix, J. E. (1981). Cytokinin-induced wall extensibility in excised cotyledons of radish and cucumber. Plant Physiol. 66, 107–110. doi: 10.1104/pp.66.1.107

Torii, K. U., Mitsukawa, N., Oosumi, T., Matsuura, Y., Yokoyama, R., Whittier, R. F., et al. (1996). The Arabidopsis ERECTA gene encodes a putative receptor protein kinase with extracellular leucine-rich repeats. Plant Cell 8, 735–746. doi: 10.1105/tpc.8.4.735

Tsugeki, R., Ditengou, F. A., Sumi, Y., Teale, W., Palme, K., and Okada, K. (2009). NOEIN mediates auxin-dependent specification and patterning in the Arabidopsis embryo, shoot, and root. Plant Cell 21, 3133–3151. doi: 10.1105/tpc.109.088841

Uchida, N., Igari, K., Bogenschutz, N. L., Torii, K. U., and Tasaka, M. (2011). The Arabidopsis ERECTA family receptor kinases mediate morphological alterations stimulated by activation of NB-LRR-type UNI proteins. Plant Cell Physiol. 52, 804–814. doi: 10.1093/pcp/pcp032

Uchida, N., Lee, J. S., Horst, R. J., Lai, H. H., Kajita, R., Kakimoto, T., et al. (2012). Regulation of inflowence architecture by intertissue layer lignin-receptor communication between endodermis and phloem. Proc. Natl. Acad. Sci. U.S.A. 109, 6337–6342. doi: 10.1073/pnas.1117537109
Uchida, N., Shimada, M., and Tasaka, M. (2013). ERECTA-family receptor kinases regulate stem cell homeostasis via buffering its cytokinin responsiveness in the shoot apical meristem. *Plant Cell Physiol.* 54, 343–351. doi: 10.1093/pcp/ps3109

Uyttewaal, M., Burian, A., Alim, K., Landrein, B., Borowska-Wykręt, D., Dedieu, A., et al. (2012). Mechanical stress acts via katanin to amplify differences in growth rate between adjacent cells in *Arabidopsis*. *Cell* 149, 439–451. doi: 10.1016/j.cell.2012.02.048

Vieten, A., Sauer, M., Brewer, P. B., and Friml, J. (2007). Molecular and cellular aspects of auxin-transport-mediated development. *Trends Plant Sci.* 12, 160–168. doi: 10.1016/j.tplants.2007.03.006

von Schwartzenberg, K., Núñez, M. F., Blaschke, H., Dobrev, P. I., Novák, O., Motyka, V., et al. (2007). Cytokinins in the bryophyte Physcomitrella patens: analyses of activity, distribution, and cytokinin oxidase/dehydrogenase overexpression reveal the role of extracellular cytokinins. *Plant Physiol.* 145, 786–800. doi: 10.1104/pp.107.103176

Wang, T., Park, Y. B., Caporini, M. A., Rosay, M., Zhong, L., Cosgrove, D. J., et al. (2013). Sensitivity-enhanced solid-state NMR detection of expansin’s target in plant cell walls. *Proc. Natl. Acad. Sci. U.S.A.* 110, 16444–16449. doi: 10.1073/pnas.1316290110

Werner, T., Motyka, V., Laucou, V., Smets, R., Van Onckelen, H., and Schmülling, T. (2003). Cytokinin-deficient transgenic *Arabidopsis* plants show multiple developmental alterations indicating opposite functions of cytokinins in the regulation of shoot and root meristem activity. *Plant Cell* 15, 2532–2550. doi: 10.1105/tpc.0114928

Williamson, R. E. (1990). Alignment of cortical microtubules by anisotropic wall stresses. *Aust. J. Biol. Sci.* 17, 601–613. doi: 10.1071/PP9900601

Willige, B. C., Ahlers, S., Zourelidou, M., Barbosa, I. C., Demarsy, E., Trevisan, M., et al. (2013). D6PK AGCVIII kinases are required for auxin transport and phototropic hypocotyl bending in *Arabidopsis*. *Plant Physiol.* 159, 1739–1746. doi: 10.1105/tpc.113.123833

Wolf, S., van der Does, D., Ladwig, F., Sticht, C., Kolbeck, A., Schürholz, A. K., et al. (2014). A receptor-like protein mediates the response to pectin modification by activating brassinosteroid signaling. *Proc. Natl. Acad. Sci. U.S.A.* 111, 15261–15266. doi: 10.1073/pnas.1322979111

Wymer, C. L., Wymer, S. A., Cosgrove, D. J., and Cyr, R. J. (1996). Plant cell growth responds to external forces and the response requires intact microtubules. *Plant Physiol.* 110, 425–430. doi: 10.1104/pp.110.2.425

Xiao, C., Somerville, C., and Anderson, C. T. (2014). POLYGALACTURONASE INVOLVED IN EXPANSION1 functions in cell elongation and flower development in *Arabidopsis*. *Plant Cell* 26, 1018–1035. doi: 10.1105/tpc.114.123908

Xu, T., Wen, M., Nagawa, S., Fu, Y., Chen, J. G., Wu, M. J., et al. (2010). Cell surface- and rho GTPase-based auxin signaling controls cellular interdigitation in *Arabidopsis*. *Cell* 143, 99–110. doi: 10.1016/j.cell.2010.09.003

Yanai, O., Shani, E., Dolezal, K., Tarkowski, P., Sablowski, R., Sandberg, G., et al. (2005). *Arabidopsis* KNOXI proteins activate cytokinin biosynthesis. *Curr. Biol.* 15, 1566–1571. doi: 10.1016/j.cub.2005.07.060

Yang, Y., Hammes, U. Z., Taylor, C. G., Schachtman, D. P., and Nielsen, E. (2006). High-affinity auxin transport by the AUX1 influx carrier protein. *Curr. Biol.* 16, 1123–1127. doi: 10.1016/j.cub.2005.07.060

Yoshida, S., Mandel, T., and Kuhlemeier, C. (2011). Stem cell activation by light guides plant organogenesis. *Genes Dev.* 25, 1439–1450. doi: 10.1101/gad.631211

Zhao, Y. (2008). The role of local biosynthesis of auxin and cytokinin in plant development. *Curr. Opin. Plant Biol.* 11, 16–22. doi: 10.1016/j.postb.2007.10.008

Zhao, Z., Andersen, S. U., Ljung, K., Dolezal, K., Miotk, A., Schultheiss, S. J., et al. (2010). Hormonal control of the shoot stem-cell niche. *Nature* 465, 1089–1092. doi: 10.1038/nature09126

Zhu, Y., Wang, Y., Li, R., Song, X., Wang, Q., Huang, S., et al. (2010). Analysis of interactions among the CLAVATA3 receptors reveals a direct interaction between CLAVATA2 and CORYNE in *Arabidopsis*. *Plant J.* 61, 223–233. doi: 10.1111/j.1365-313X.2009.04049.x

Zourelidou, M., Müller, I., Willige, B. C., Nill, C., Iikumaru, Y., Li, H., et al. (2009). The polarly localized D6 PROTEIN KINASE is required for efficient auxin transport in *Arabidopsis thaliana*. *Development* 136, 627–636. doi: 10.1242/dev.028365

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

**Copyright © 2015 Tameshige, Hinakawa, Torii and Uchida. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) or licensor are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.**