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To cite this version: Tatsuaki Goh, Koichi Toyokura, Darren Wells, Kamal Swarup, Mayuko Yamamoto, et al.. Quiescent center initiation in the Arabidopsis lateral root primordia is dependent on the SCARECROW transcription factor. Development (Cambridge, England), Company of Biologists, 2016, 143 (18), pp.3363-3371. 10.1242/dev.135319. hal-03169624

HAL Id: hal-03169624
https://hal.archives-ouvertes.fr/hal-03169624
Submitted on 28 May 2021

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Quiescent center initiation in the *Arabidopsis* lateral root primordia is dependent on the SCARECROW transcription factor

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**ABSTRACT**

Lateral root formation is an important determinant of root system architecture. In *Arabidopsis*, lateral roots originate from pericycle cells, which undergo a program of morphogenesis to generate a new lateral root meristem. Despite its importance for root meristem organization, the onset of quiescent center (QC) formation during lateral root morphogenesis remains unclear. Here, we used live 3D confocal imaging to monitor cell organization and identity acquisition during lateral root development. Our dynamic observations revealed an early morphogenesis phase and a late meristem formation phase as proposed in the bi-phasic growth model. Establishment of lateral root QCs coincided with this developmental phase transition. QC precursor cells originated from the outer layer of stage II lateral root primordia, within which the SCARECROW (SCR) transcription factor was specifically expressed. Disrupting SCR function abolished periclinal divisions in this lateral root primordia cell layer and perturbed the formation of QC precursor cells. We conclude that *de novo* QC establishment in lateral root primordia operates via SCR-mediated formative cell division and coincides with the developmental phase transition.

**KEY WORDS:** Lateral root organogenesis, Quiescent center, SCARECROW, 3D live imaging, *Arabidopsis thaliana*

**INTRODUCTION**

The plasticity of plant root system architecture provided by post-embryonic lateral root (LR) formation greatly contributes to its adaptability to environmental conditions (Bao et al., 2014). LRs facilitate nutrient and water acquisition by increasing soil exploration. While primary root initiation, organization and growth have been extensively studied, the molecular and cellular mechanisms that control the patterning of new lateral root primordia (LRPs) are still poorly characterized (Tian et al., 2014a). Root growth results from the activity of the root apical meristem (RAM), a group of proliferating cells organized around a central stem cell niche (SCN). The RAM of the primary root (PR) is created during early embryogenesis through formative cell divisions and initial cell identity is maintained by an organizing center termed the quiescent center (QC) (Perilli et al., 2012; ten Hove et al., 2015). A number of regulatory mechanisms have been identified that control QC establishment and maintenance in the PR, especially in the model plant *Arabidopsis thaliana*. The phytohormone auxin controls the specification of the hypophysis (the QC precursor cell) during embryogenesis and later maintains QC function in seedling roots with the AP2-domain *PLETHORA* (*PLT*) transcription factors (Moller and Weijers, 2009; ten Hove et al., 2015). The maintenance of the QC and SCN during post-embryonic primary root growth relies on the activity of *PLT* and GRAS-family transcription factors *SHORT-ROOT* (*SHR*) and *SCARECROW* (*SCR*) in combination with an auxin gradient (Bennett and Scheres, 2010; Perilli et al., 2012).

Despite similarities between primary and lateral root meristems, these structures are generated in different tissue and genetic contexts, and many of the processes governing the generation of a new root meristem in LRP remains to be elucidated (Lavenus et al., 2013; Tian et al., 2014a). In particular, little is known about the patterning processes controlling *de novo* establishment of the QC and SCN in the developing LRP (Laskowski et al., 1995; Tian et al., 2014a). In *A. thaliana*, LRs originate from a subset of approximately six pericycle cells that divide and form a new root apical meristem with a radially symmetrical structure akin to the PR (Lavenus et al., 2013). A pioneering study of *Arabidopsis* lateral root development by Ian Sussex and co-workers originally proposed that LR organogenesis occurs in two successive steps: first, an early morphogenesis phase during which a primordium composed of three to five layers of approximately isodiametric cells is generated; second, a meristem formation phase, during which cell identity patterning and meristem organization occurs, generating the characteristic tissue structure of the root apex (Laskowski et al., 1995). Later, Malamy and Benfey (1997) performed an extensive analysis of LRP morphogenesis and proposed eight developmental stages (stage I to stage VII and emergence) based on anatomical criteria and these structural milestones have been confirmed in later studies (Lucas et al., 2013; von Wagenheim et al., 2016). In summary, LRP formation is initiated when asymmetric anticlinal cell divisions of founder cells produce pairs of abutting small cells flanked by longer cells (stage I; Goh et al., 2012). Next, the central smaller cells undergo three further rounds of periclinal cell divisions to create a four-layered primordium (stages II to IV). During stages V and VI, the LRP acquires a cellular organization similar to the primary RAM. At the emergence stage, the LRP finally breaks through overlying root tissues and enters the soil (Lavenus et al., 2013; Malamy and Benfey, 1997). Thus, an anatomical organization reminiscent of a presumptive organizing center was first observed in longitudinal sections of stage VI lateral root
primordia. However, the dynamics of QC establishment during LRP development has remained elusive (Tian et al., 2014a).

Here, we investigated further the classical two-step LRP developmental model formulated by Sussex and co-workers (Laskowski et al., 1995), focusing on the mechanisms controlling de novo QC formation during LRP development. We developed a 3D time-lapse confocal laser-scanning microscopy imaging approach to analyze development of living lateral root primordia. We observed that QC formation, as reported by QC marker gene expression, occurs at the transition between the early morphogenesis phase and the later meristem organization phase of LRP development. These two events also coincide with a 3D organ shape change from bilateral to radial. Cell lineage analysis revealed that the QC originates from the outer layer of stage II LRP. We report that the GRAS family transcription factor SCR regulates QC formation by controlling formative periclinal cell divisions that give rise to QC precursor cells. We conclude that de novo QC establishment in LR depends on SCR expression in the outer layer of stage II primordia and coincides with a developmental phase transition.

RESULTS

LR formation exhibits a bi-phasic pattern of growth

To understand the molecular and cellular mechanisms controlling LR organogenesis, a confocal laser scanning microscopy (CLSM)-based 3D time-lapse imaging approach was developed using a transgenic line ubiquitously expressing a plasma membrane-localized yellow fluorescent protein (YFP)-tagged reporter termed WAVE131Y (Geldner et al., 2009). Images were taken at 10 min intervals as z-stacks (2 µm step) over a 24 h period. This strategy allowed us to observe the entire process of LRP morphogenesis spanning early developmental stages up to organ emergence at high temporal and spatial resolution and was compatible with the monitoring of live functional cell markers. Precise analysis of a time-lapse 3D image series of developing LRP obtained using this method was consistent with the 2D anatomical stages described by Malamy and Benfey (1997). Importantly, our imaging technique also allowed us to explore the kinetics of LRP morphogenesis throughout these stages (Fig. 1A,B and Movie 1). Following anticalinal divisions of founder cells creating a one-layered stage I primordium, later pericalinal divisions generate a two-layered LRP (stage II; Fig. 1A, t=0:00), which subsequently undergoes new anticalinal divisions to produce a stage II primordium composed of small cells (Fig. 1A, t=4:00, white arrowheads). A second round of pericalinal divisions in the outer layer of stage II (Fig. 1A, t=7:00, white arrowhead) then creates a three-layered primordium (termed stage III). A third round of pericalinal divisions (this time in the innermost cell layer) produces a four-layered LRP (termed stage IV; Fig. 1A, t=9:30, white arrowhead). In summary, during this early morphogenesis phase (stages I to IV), well-coordinated anticalinal and pericalinal cell divisions generate a four-layered LRP. Stage V was characterized by anticalinal divisions at the flanking cells of outer layers (Fig. 1A, t=14:00, arrowheads) and elongation of inner cells (Fig. 1A, t=14:00 and 15:00, denoted by two-directional arrows). Stage VI LRP exhibited pericalinal and anticalinal cell divisions that produced the endodermal and cortical layers, and pericalinal cell divisions in the outermost layer that will give rise to the root cap (Fig. 1A, t=21:00, arrowheads; Fig. S1). Thus, through characteristic cell divisions and cell elongation events in stage V and VI, an anatomically recognizable meristematic structure is formed as early as stage VI, consistent with results initially described by Malamy and Benfey (1997).

During the early LRP morphogenesis phase (stages I to IV), cell divisions remained constrained within the space between underlying protoxylem and overlying endodermal tissues (Fig. 1A,B). Both protoxylem and endodermal cells contain lignified walls (termed the Casparian strip in the latter case) that provide these tissues with structural rigidity (Naseer et al., 2012).

![Fig. 1. Cellular patterning and QC establishment during Arabidopsis LR primordium development.](image-url)

(A) Time-lapse image series of LR primordium development visualized using WAVE131Y (plasma membrane, yellow) and QC25::CFP (QC marker, cyan). White arrowheads and two-directional arrows indicate the characteristic cell divisions and cell elongation, respectively. The elapsed time (h:min) after the start of observation and developmental stage are indicated on each panel. See also Movie 1. Scale bar: 50 µm. (B) Cell lineage map of the LRP shown in A. The inner and outer layers of stage II (t=0:00) are shown in light blue and pink, respectively. The cells derived from each layer are indicated by the same color. Dark blue indicates outer layer-derived cells that showed a QC25::CFP signal. (C) Quantification of LRP height (blue) and QC25::CFP fluorescence intensity (red). QC25::CFP intensity was quantified at the center cells of the second outermost layer. LRP developmental stages are categorized according to a previous paper (Malamy and Benfey, 1997). (D,E) Front view (a,b,d and e) and top-down view (c and f) of digitally sliced images of A [t=9:30 (D) and 14:00 (E)]. The white dotted lines in the side view images indicate the positions of the sliced planes. White arrowheads indicate the longitudinal radial cell divisions at the outermost (d) or second outermost layer (e) of the stage V LRP (E, t=14:00). Scale bars: 50 µm.
These rigid cell walls, especially the Casparian strip, provide mechanical constraints on LRPs, which impact the LRP morphogenesis (Lucas et al., 2013; Vermeer et al., 2014). Consistent with this, our time-lapse image data revealed that the rate of organ outgrowth (inferred from changes in its height) remained slow until stage V (Fig. 1C), and LRP shape was flattened when the LRP was passing through the endodermal layer (Fig. 1A, t=7:00, 9:30 and 14:00). Then, the growth rate of LRP significantly accelerated (Fig. 1C) and LRP changed to dome-shaped from the end of stage V (meristem formation phase; Fig. 1A, t=15:00) (Kumpf et al., 2013; Lucas et al., 2013). This expansion of the LRP seems principally caused by axial elongation of cells at the base of the primordium (depicted by two-directional arrows in Fig. 1A, t=14:00 and 15:00).

Taken together, these time-lapse observations of developing primordia suggested that LRP formation operates in two developmental phases: an early morphogenesis phase (stages I to IV) during which a four-layered LRP is formed, constrained between the xylem pole and the endodermis, and a later meristem formation phase (stage V onwards) characterized by the onset of a mature meristem structure and rapid organ outgrowth. This is consistent with the hypothesis that LRP formation is a bi- phasic growth process as originally proposed by Laskowski et al. (1995), with phase transition occurring at stage V as described by Malamy and Benfey (1997).

### 3D cell division orientation and LRP shape change coincides with a developmental phase transition

We previously reported that LRPs initially exhibit bilateral symmetry that later changes to radial symmetry, adopting a cylindrical shape similar to the PR (Lucas et al., 2013). Tangential divisions at the flanking side contribute to the 3D LRP shape change by creating a ring of cells surrounding the central dividing cells (Lucas et al., 2013). In order to better understand the contribution of division plane orientation to the 3D LRP shape and its relationship with the LRP developmental phase transition, we monitored nuclear dynamics by employing our time-lapse imaging system with the nuclear-localized reporter line pRPS5a::H2B:tdTomato (Adachi et al., 2011) and then tracked LRP nuclei movement and cell divisions (Fig. 2A-F, Fig. S2). This 4D tracking of nuclei showed the contributions of daughter cells derived from pericycle cell files adjacent to the xylem pole in the 3D LRP structure and revealed that LRPs are predominantly formed from cells in three files of pericycle cells (Fig. 2A-F, Movie 2). Consistent with previous analysis (Kurup et al., 2005; von Wangenheim et al., 2016), the central pericycle file provided all of the cells in the central median plane (green), whilst cells derived from adjacent pericycle files (red and orange) contributed to the LRP flanks (Fig. 2A-F, Movie 2). Until stage IV, cells from the central cell file underwent three rounds of periclinal cell division to create a four-layered primordium (t=12:00, Fig. 2A,B). Around the phase transition (stage V, t=16:00, Fig. 2C,D, Movie 2), an abrupt reorientation of the cell division plane (termed longitudinal) occurred in the median file of the LRP, contributing to primordium widening (t=22:00, Fig. 2E,F, white arrows). Careful analysis of cell division patterns in WAVE131Y-expressing LRP revealed that new longitudinal planes of cell divisions indeed promoted LRP widening at stage V (Fig. 1E, tangential sections d and e, arrowheads). Hence, cell division plane re-orientation at stage V contributes to 3D LRP shape change towards a cylindrical structure, concomitant with the early-to-late LRP morphogenesis phase transition. Thus, a developmental transition takes place at stage V during LRP development, and encompasses two events: the change from an early four-layer primordium generation phase to a later meristem organization phase, and a switch from bilateral to radial organ growth.

**QC formation occurs simultaneously with an LRP developmental transition at stage V**

In the PR, QC cells function as an organizing center regulating the activity and maintenance of the stem cell niche (SCN; Bennett and Scheres, 2010; Perilli et al., 2012). Despite its fundamental importance for meristem formation and subsequent growth of new LRs, nothing is known about the spatio-temporal regulation of post-embryonic formation of QC cells. To address this, we initially...
studied the expression dynamics of the QC-specific reporter line QC25::CFP (ten Hove et al., 2010) using our time-lapse imaging system. QC25::CFP expression was first detected in cells at the center of the second outermost layer at stage IV/V, and the reporter signal was enhanced at a later stage (Fig. 1A-E, Movie 1). The expression of QC25::CFP was initiated before the characteristic cell divisions and accelerated organ outgrowth at the later meristem formation phase (Fig. 1A,C, Movie 1).

To confirm this observation and explore how QC formation is related to 3D structural changes of the LRP, we performed nuclear tracking in developing primordia expressing both pWOX5::n3GFP and pRPS5a::H2B:tdTomato markers (Fig. 2G-Z, Movie 3). The second QC marker pWOX5::n3GFP exhibited an identical spatial and temporal expression pattern to QC25::CFP in the LRP (Fig. 1 and Fig. 2G-K; Movies 1 and 3), initially being detected in the central cells of the second outermost layer of stage IV/V just prior to phase transition (t=14:00, Fig. 2L,N,S,X). Importantly, the longitudinal divisions occurred simultaneously with expression of WOX5 (Fig. 2J,O,T,Y, Movie 4) and QC25::CFP (Fig. 1E). Digital cross-sections revealed that the expression of both QC reporters was detected in a subset of four LRP cells located in the center of the second outermost layer of stage V primordia (Fig. 1E, tangential section e; Fig. 2O,P,T,U,Y,Z; Movie 4), suggesting that the central single cell file produced a group of four QC cells by reorientation of the cell division plane (i.e. longitudinally) at stage V. Based on the timing of induction of both QC25 and WOX5 markers, we conclude that QC establishment coincides with the developmental transition from an initial basic cellular organization with bilateral symmetry to the later meristem formation phase with progressive acquisition of radial symmetry.

**QC cells originate from the outer layer of stage II LRP**

To help determine how the QC is established during the earlier stages of development, we tracked cell lineages in developing LRP using our time-lapse series of CLSM images (Fig. 1B). Our analysis revealed that vascular and pericycle tissues originated from the inner layer of stage II LRP (indicated in pink in Fig. 1B), whereas the outer layer of stage II LRP gave rise to the epidermis, ground tissues (endodermis and cortex) and root cap tissues (shown in light blue in Fig. 1B; Fig. S1). Our dynamic cell-fate analysis validated the lineage model proposed by Malamy and Benfey (1997). In addition, our analysis revealed that QC cells are derived from the outer layer of stage II LRP. More precisely, the central daughter cells of the second outermost layer, after the second periclinal division of the outer layer of stage II LRP, were specified as QC precursor cells, in which the expression of QC markers was initiated at stage V (Fig. 1A,B; QC cells are shown in dark blue in Fig. 1B). Hence, the differentiation of inner and outer layers in the stage II LRP appears to be an important event preceding QC specification and subsequent root meristem patterning.

**SHR and SCR expression domains distinguish inner and outer LRP layers**

Earlier studies have reported that the GRAS-type transcription factor SCARECROW (SCR) is one of the earliest genes exhibiting differential LRP expression, specifically in the outer layer of stage II primordia (Malamy and Benfey, 1997). SCR interacts with another GRAS-type transcription factor, SHORT-ROOT (SHR), to regulate SCN maintenance, ground tissue formation and organ growth in the PR (Fisher and Sozzani, 2016). Using our time-lapse imaging system, a functional pSCR::GFP:SCR marker [in a scr-3 mutant background (Gallagher et al., 2004)] was first detected in stage II LRP specifically in the outer layer (Fig. 3A, t=4:00 and 8:00; Fig. 3F; Movie 5). Following periclinal division of the outer layer of stage II LRP, the GFP:SCR protein was initially detected in both daughter cell layers (Fig. 3A, t=12:00; Fig. 3G), but the signal gradually disappeared from the outermost layer (Fig. 3A, t=16:00), while it was maintained in the nuclei of cells within the second outermost layer of the LRP after stage III (Fig. 3A, t=20:00; Fig. 3H). The second outermost layer-specific expression of the SCR gene was confirmed using a transcriptional pSCR::GUS:GFP reporter (Fig. 3C-E). Consistent with previous reports (Malamy and Benfey, 1997; Tian et al., 2014b), our dynamic live confocal observations revealed how the SCR expression domain forms during LRP development.

**SCR transcription is largely dependent on SHR (Helariutta et al., 2000; Levesque et al., 2006).** In primary RAMs, the SHR gene is expressed in stele cells (including the pericycle), where the SHR protein is localized in the cytosol and nucleus, but the SHR protein moves via plasmodesmata to nuclei of adjacent QC and endodermal cells, where it activates SCR expression (Nakajima et al., 2001). In stage I LRP, the functional SHR:GFP protein expressed under the control of its own regulatory region (pSHR::SHR:GFP) in the shr-2 mutant background (Nakajima et al., 2001) was detected very weakly in all cells (Fig. 3B, Movies 6 and 7, t=0:00). In stage II LRP, the SHR:GFP protein signal gradually increased in cells of the inner layer while it was weakly detected in the outer layer (Fig. 3B, t=4:00 and 8:00), where the SHR:GFP proteins locate in the nuclei (Fig. 3B,L). From stage III onwards, the SHR:GFP protein signal remained high in the inner layer-derived tiers, and gradually increased in the nuclei of cells of the second outermost layer directly overlying SHR-expressing inner layer-derived cells (Fig. 3B, t=12:00-20:00, M,N, Movies 6 and 7). The inner layer-specific expression of the SHR gene was confirmed using a transcriptional pSHR::GUS reporter (Fig. 3I-K), consistent with published results (Lucas et al., 2011). The appearance of SHR:GFP protein in cell nuclei in the second outermost layer of the LRP coincided with an enhanced level of GFP:SCR signal in those cells (Fig. 3A,B), consistent with SCR transcription being largely SHR dependent (Helariutta et al., 2000; Levesque et al., 2006). Thus, our imaging system helped refine our knowledge of SCR and SHR expression dynamics in developing primordia and revealed that in stage II LRP, the SHR and SCR transcriptional domains delineate the inner and outer cell layers, respectively, which might be functionally important for further primordium morphogenesis.

**The scr mutation disrupts QC establishment**

To determine the functional importance of SCR outer layer-specific expression in stage II primordia, we analyzed LRP morphogenesis in the scr-3 mutant using time-lapse imaging (Figs 4 and 5). In wild-type plants, periclinal divisions in stage II LRP occurred according to a regular sequence: cells divided initially in the outer layer, and subsequently in the inner layer (Fig. 1A, t=7:00 and 9:30; Movie 1). After stage II periclinal division, two or three rounds of cell divisions were observed in the outermost layer-derived cells over the following 20 h (Fig. 5A, blue box and nuclei; Fig. S3). Slower divisions were observed in the cells derived from the second outermost layer of stage IV in the same time period (Fig. 5A, red box and nuclei; Fig. S3). In contrast, cell divisions in the outer layer of the scr-3 mutant LRP were largely abolished during early primordium development (Fig. 4A,B, t=6;00; Movie 8), while the inner layer underwent periclinal divisions. Later, cell divisions in the outer layer-derived periclinal divisions of the primordium occurred only once in a small number of central cells during the 20 h of our time-lapse...
observation, although inner layer-derived cells continued to divide in a wild-type fashion (Fig. 4A, B, t = 11:30 and 18:00; Fig. 5B; Fig. S3; Movie 8). As a consequence, after stage II, it is difficult to assign precise stages to developing \textit{scr-3} primordia according to Malamy and Benfey’s nomenclature. Hence, \textit{SCR} appears to promote the second round of periclinal cell divisions in the outer layer of the stage II LRP, as well as subsequent divisions of the outer layer derivatives, whereas inner layer cell divisions are independent of \textit{SCR} function.

In order to confirm the specific cell division defects in the outer layer of the \textit{scr-3} mutant, we monitored the spatial activity of the \textit{SCR} promoter (pSCR::GUS:GFP) during LRP development. Whilst pSCR::GUS:GFP signal was clearly enhanced in the second outermost layer of wild-type LRPs at stage V (Fig. 4C, D), it appeared more uniform in \textit{scr-3} cells derived from presumptive derivatives of the stage II outermost layer at approximately the same stage (Fig. 4E, F). We also observed similar defects in the periclinal cell division in the outer layer and spatial pattern of \textit{SCR} promoter activity in \textit{shr-2} (Fig. S4), consistent with the mutant’s previously reported severe LRP patterning defects (Lucas et al., 2011). These observations suggested that defects in periclinal divisions in the stage II outermost layer of \textit{scr-3} and \textit{shr-2} LRP disrupt the correct spatial regulation of \textit{SCR} expression during later LRP development. Based on these data, we conclude that periclinal divisions in the outer layer of stage II LRP (some of which generated the future QC cells) are regulated by \textit{SCR} and \textit{SHR}.

Our earlier cell lineage analysis revealed that the periclinal divisions in the outer layer of the stage II LRP are important for producing QC precursor cells (Fig. 1A, B). Thus, disrupting periclinal cell division in the outer layer of the \textit{scr-3} stage II LRP would compromise QC formation. Indeed, nuclear expression of the \textit{pWOX5::n3GFP} QC marker was undetectable in the \textit{scr-3} LRP prior to organ emergence (Fig. 6). At 24 h, WOX5 promoter activity was weakly detected at a QC-like position, after which reporter expression was strongly detected at later time points (Fig. 6). This observation suggested that specific expression of \textit{SCR} in the outer layer of stage II promotes formative periclinal cell divisions to produce QC precursor cells and subsequent QC establishment in the LRP.

Nevertheless, \textit{scr-3} LRP continued to develop as a result of the division of cells derived from the inner layer, and eventually, cells occupying similar positions to wild-type QC cells in \textit{scr-3} LRP expressed the \textit{pWOX5::n3GFP} QC marker, albeit considerably later than the wild type (Fig. 6, t = 28:30 and 34:00, red arrowheads). Consistent with this observation, the \textit{scr} mutant created mature LR s, although they were shorter than those in the wild type (Fig. S5), possibly because of later defects in SCN maintenance by similar mechanisms to the PR (Sabatini et al., 2003). Interestingly, tracking the origin of the QC marker-positive cells in the \textit{scr-3} mutant revealed that they were derived from inner layer cells of the stage II LRP (Fig. 6B, shown in pink). Our observations suggest that QC formation in the LRP is normally dependent on \textit{SCR}-mediated
periclinal cell division in the outer layer of the stage II LRP. However, when the normal pattern of QC establishment is defective, QC cells still eventually establish, albeit independent of SCR regulation via a distinct LRP cell lineage.

**DISCUSSION**

LR formation represents a highly integrated and dynamic process that transforms LR founder cells into new root meristems. Here, we describe de novo establishment of QC and meristem organization during LRP morphogenesis. A 3D time-lapse confocal imaging approach revealed that LRP development operates in a bi-phasic manner: first, from stages I to IV, periclinal and anticlinal cell divisions create a simple four-layered primordium with respect to the main growth axes of pericycle cells. From stage V onwards, more-complex cell division patterning contributes to meristem formation accompanied with accelerated growth and 3D shape change to a radially cylindrical structure similar to the PR. Our time-lapse analyses of live LRP development are consistent with previously reported results (Laskowski et al., 1995; Malamy and Benfey, 1997) and further support the model of a biphasic morphogenesis process initially proposed by Laskowski et al. (1995) (Fig. 7).

Our confocal-based time-lapse imaging system allowed us to analyze live lateral root development with high spatio-temporal resolution. This approach is complementary to the light sheet fluorescence microscopy (LSFM)-based imaging technique reported by von Wangenheim and co-workers (2016). Both techniques enable 4D monitoring of living lateral root primordia. While LSFM offers 4D visualization of the root sample with reduced exposure to laser sources, our confocal-based approach provides advantages such as high resolution and flexible control of multi-colored imaging, by enabling visualization of multiple reporters simultaneously.

Our study also revealed that the transition between the two major phases of LR development, namely early morphogenesis phase and late meristem formation phase, occurs in stage V primordia and coincides with the onset of QC marker gene expression in central cells of the second outermost layer. Despite previously reported observations suggesting earlier onset of WOX5 expression during LR development (Ditengou et al., 2008), our repeated analyses of two new QC markers (pWOX5::m3GFP and QC25::CFP) support the conclusion that QC identity is established around stage V during LRP development.

Our study also reveals that QC establishment in LRs relies on the differentiation of the inner and outer layers in stage II primordia.
controlled by two GRAS-family transcription factors, SCR (outer layer) and SHR (inner layer). It is plausible that, as observed in the primary root meristem, SHR protein movement from the presumptive stelle of stage II primordium to the overlying cell layer induces SCR expression and that SCR-SHR interaction later restricts SCR expression domain to the second outermost layer of the developing LRP (Cui et al., 2007). However, the precise mechanisms regulating SHR expression, migration and transcriptional activity in the context of lateral root development remain to be elucidated.

The SCR-expressing outer LRP layer produces QC precursor cells via SCR-regulated periclinal cell divisions. These observations are reminiscent of two functional properties of SCN regulation in the PR. First, WOX5 expression in the PR meristem was shown to depend on the SCR/SHR regulation pathway (Sarkar et al., 2007). Thus, despite the differences in the tissue context of both events, regulation of WOX5 expression by the SHR/SCR module seems to be conserved between primary and lateral root meristem formation. Second, earlier work on the PR has shown that SHR and SCR regulate formative cell divisions in root ground tissue initial cells, generating endodermal and cortical layers (Cruz-Ramirez et al., 2012; Sozzani et al., 2010). In this study, we report that in stage II LR primordia, SCR also regulates the formative periclinal division of the outer layer, preceding QC specification. This suggests that cell division pattern for QC establishment is regulated differently during LR development and embryogenesis in Arabidopsis (Wysocka-Diller et al., 2000) and that, while SCR is not strictly required for LR QC establishment, ‘normal’ QC-forming formative divisions in the lateral root primordium depend on SCR function.

Ian Sussex and co-workers originally proposed that the formation of a LR meristem is a two-step process (Laskowski et al., 1995) and hypothesized that there is an unknown developmental transition event between these two phases. We report that QC formation correlates with the transition from an early morphogenesis phase to a later meristem formation phase at stage V and with bilateral to radial 3D organ shape change. Before that stage, the SCR/SHR module controls the initial inner/outer patterning of stage II primordium and promotes the formative periclinal cell division of the outer layer that precedes QC formation. After that stage, QC specification might contribute to orchestrate further steps of root meristem organization in the developing primordium. Primary root QC cells organize SCN activity and maintenance by controlling phytohormone distribution and the spatio-temporal activity of transcription factors (Perilli et al., 2012; ten Hove et al., 2015). It will be interesting to analyze how QC establishment influences meristem organization and maintenance in the second phase of LRP development, and to compare it with the regulatory networks operating in the primary root apex. Interestingly, despite being severely impaired in outer layer-derived cell divisions during the earlier developmental phase, ultimately, the scr mutant could still establish a QC at a similar position to that in the wild type. This observation suggests that cells in the early LRP of the scr mutant still have competency for QC establishment, which might have similar regulatory mechanisms to root regeneration (Sena et al., 2009; Xu et al., 2006). This emphasizes the robustness of LR

Fig. 6. The scr mutation disrupts the normal pattern of QC establishment in LRP. (A) Time-lapse image series of LRP development in pWOX5::n3GFP AUX1-YFP in the scr-3 mutant background. A nuclear signal indicates pWOX5::n3GFP expression (indicated by red arrowheads). The elapsed time (h:min) from the start of observation is indicated in each panel. Scale bar: 50 µm. (B) Cell lineage map of the LRP shown in A. The inner and outer layers of stage II (=0:00) are colored light blue and pink, respectively. Red indicates inner layer-derived cells that have a pWOX5::n3GFP signal.

Fig. 7. Schematic model of Arabidopsis LR organogenesis. LR development is biphasic with an initial morphogenesis phase to form basic four-layered LRP followed by meristem formation phase as initially proposed by Laskowski et al. (1995). The transition from bilateral to radial 3D organ shape also coincides with the transition from early morphogenesis to late meristem formation phases. The GRAS-family transcription factor, SCARECROW (SCR) is specifically expressed in the outer layer of stage II and regulates the formation of precursor cells of QC through SCR-mediated periclinal cell divisions (indicated by yellow dashed line at stage III). QC establishment occurs simultaneously with and facilitates the developmental phase transition of LRP at stage V.
meristem patterning mechanisms with respect to cell lineage. We hypothesize that QC cell specification in the LR is regulated by yet to be determined positional information (e.g. phytohormones, mobile signals) and a dynamic gene regulatory network (Lavenus et al., 2015; Voss et al., 2015). Further analyses will help to address the SCR-independent patterning mechanisms for de novo QC specification in the LRP and shed light on the functional importance of this new stem cell niche for LRP development.

MATERIALS AND METHODS

Plant materials and growth conditions

The A. thaliana accession Col-0 was used throughout the experiments. The following transgenic plants were used: QC25::CFP (ten Hove et al., 2010), WAVE1:11Y (Geldner et al., 2009), pRPS5a:H2B::tdTomato (Adachi et al., 2011), pSCR::GFP:SCR (scr-3) (Gallagher et al., 2004), pSHR::GUS (shr-2) (Nakajima et al., 2001), pSHR::GUS (Helairetta et al., 2000), shr-2 and scr-3 (Fukaki et al., 1998) and AUX1::YFP (Swarup et al., 2004). Seeds were germinated under sterile conditions on 1× Murashige and Skoog medium solidified with 0.5% gellan gum containing 0.5 g/l MES-KOH (pH 5.8), – EDTA, 5 mM potassium ferrocyanide, 5 mM potassium ferricyanide, 0.1% Triton X-100 and 0.5 mg/ml 5-bromo-4-chloro-3-indolyl-b-D-glucuronic acid (X-Gluc). Whole-mount clearing preparation of roots was performed using chloral hydrate. Samples were observed with a Leica DM6000 microscope equipped with Nomarski optics (Leica Microsystems).

Acknowledgements

We thank Philip N. Benfey (Duke University), Ben Scheres (Wageningen UR), Sachihiro Matsunaga (Tokyo University of Science) and Tsyoshibi Nakagawa (Shimane University) for providing experimental materials. We also thank Yuichiro Imai (Olympus) for providing valuable advice and technical support for the time-lapse imaging and lighting system, and Yoshiie Okamoto and Shiori Sera for technical assistance.

Competing interests

The authors declare no competing or financial interests.

Author contributions

T.G., L.L., M.J.B. and S.G. designed the research; T.G. and K.S. performed the research; T.G., K.T., D.M.W., M.Y., T.M., H.F. and S.G. contributed new tools; T.G., L.L., M.J.B. and S.G. analyzed the data; T.G., K.T., H.F., L.L., M.J.B. and S.G. wrote the paper; all authors read and approved the paper.

Funding

This work was supported by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) through a JSPS Research Fellowship for Young Scientists [21J20279 to T.G.]; a Grant-in-Aid for Scientific Research on Priority Areas [19060006 to H.F.]; and a Grant-in-Aid for Scientific Research on Innovative Areas [25113003 to H.F.].

Supplementary information

Supplementary information available online at http://dev.biologists.org/lookup/doi/10.1242/dev.135319.supplemental

References


