

RESEARCH ARTICLE

Sterols regulate endocytic pathways during flg22-induced defense responses in *Arabidopsis*

Yaning Cui^{1,2,*}, Xiaojuan Li^{1,2,*}, Meng Yu^{1,2}, Ruili Li^{1,2}, Lusheng Fan³, Yingfang Zhu^{4,5} and Jinxing Lin^{1,2,‡}

ABSTRACT

The plant transmembrane receptor kinase FLAGELLIN SENSING 2 (FLS2) is crucial for innate immunity. Although previous studies have reported FLS2-mediated signal transduction and endocytosis via the clathrin-mediated pathway, whether additional endocytic pathways affect FLS2-mediated defense responses remains unclear. Here, we show that the *Arabidopsis thaliana* sterol-deficient mutant *sterol methyltransferase 1* displays defects in immune responses induced by the flagellin-derived peptide flg22. Variable-angle total internal reflection fluorescence microscopy (VA-TIRFM) coupled with single-particle tracking showed that the spatiotemporal dynamics of FLS2-GFP changed on a millisecond time scale and that the FLS2-GFP dwell time at the plasma membrane increased in cells treated with a sterol-extracting reagent when compared with untreated counterparts. We further demonstrate that flg22-induced FLS2 clustering and endocytosis involves the sterol-associated endocytic pathway, which is distinct from the clathrin-mediated pathway. Moreover, flg22 enhanced the colocalization of FLS2-GFP with the membrane microdomain marker Flot 1-mCherry and FLS2 endocytosis via the sterol-associated pathway. This indicates that plants may respond to pathogen attacks by regulating two different endocytic pathways. Taken together, our results suggest the key role of sterol homeostasis in flg22-induced plant defense responses.

KEY WORDS: Sterols, VA-TIRFM, FLS2, Spatiotemporal dynamics, Endocytosis, Plant immunity

INTRODUCTION

Plants possess a multilayered defense system of innate immunity that confers resistance against many pathogens. Plant cells have a variety of immune receptors, also known as pattern recognition receptors (PRRs), that recognize conserved microbial- or pathogen-associated molecular patterns (PAMPs) (Dodds and Rathjen, 2010; Monaghan and Zipfel, 2012; Felix et al., 1999), such as fungal chitin, and the bacterial factor elongation factor EF-Tu (Kunze et al., 2004), flagellin (Robatzek et al., 2006) and lipopolysaccharides (Mulder et al., 2006; Radutoiu et al., 2007). The *Arabidopsis thaliana* receptor kinase FLAGELLIN SENSING 2 (FLS2) is a

well-known PRR that perceives a conserved 22 amino acid domain in the N terminus of flagellin (flg22) (Mulder et al., 2006; Radutoiu et al., 2007). Upon perception of flg22, FLS2 physically associates with another leucine-rich repeat receptor-like kinase (LRR-RLK), BAK1 (BRASSINOSTEROID-INSENSITIVE 1-ASSOCIATED KINASE 1) (Heese et al., 2007; Roux et al., 2011), and is phosphorylated by BIK1 (BOTRYTIS-INDUCED KINASE 1) (Segonzac and Zipfel, 2011). Activation of FLS2 triggers a series of downstream immune responses (Asai et al., 2002; Boudsocq et al., 2010; Henry et al., 2013), including the production of reactive oxygen species (ROS), induction of defense genes, deposition of secondary compounds, such as callose, and accumulation of defense hormones (Grossie et al., 2009; Gómez-Gómez and Boller, 2000; Boudsocq et al., 2010).

Numerous reports support the concept that endocytosis of receptor kinases physically terminates signaling through degradation of receptors, sustains signaling through recycling or relays signals inside the cell through the formation of signaling endosomes (Du et al., 2013). The recycling/signaling and the degradative fates preferentially associate with different endocytic routes (Sigismund et al., 2008). In animal cells, multiple pathways of endocytosis have been identified and classified, including clathrin-dependent and clathrin-independent pathways (Doherty and McMahon, 2009). Similarly, two endocytic pathways have been found in plant cells: the clathrin-mediated and the sterol/raft-associated endocytic pathways (Fan et al., 2015). The clathrin-mediated endocytic pathway (CME) is the major and best-studied endocytic pathway in plant cells (Ortiz-Moreno et al., 2016).

The sterol/raft-associated endocytic pathway has also been described and may involve specific membrane microdomain proteins such as flotillin 1 (Flot1) (Li et al., 2012). Membrane microdomains are thought to temporally and spatially organize proteins and lipids into dynamic signaling complexes (Cacas et al., 2012). In animal and yeast cells, sterol-rich domains may function as sorting platforms for proteins that function in signal transduction, pathogen entry, secretion and endocytosis (Simons and Toomre, 2000). Sterol-associated endocytic pathways have been described in plant cells (Men et al., 2008), although the mechanisms of this pathway in plant immunity have yet to be investigated.

Here, we describe a series of investigations into the mechanism of FLS2 endocytosis, to explore the link between sterols and FLS2 dynamics in response to the plant immunity signal flg22. Phenotypic analyses showed that sterols can affect the flg22-induced immune response. Variable-angle total internal reflection fluorescence microscopy (VA-TIRFM) in combination with single-particle tracking (Li et al., 2011) showed that FLS2 is mobile and heterogeneously distributed at the plasma membrane, and that sterols affected this distribution. Furthermore, we demonstrate that the *sterol methyltransferase 1* (*smt1*) mutation does not change the homo-oligomeric state of FLS2 but does affect FLS2 cluster formation. In addition, endocytosis of FLS2 is impaired in *smt1* mutants.

¹Beijing Advanced Innovation Center for Tree Breeding by Molecular Design, Beijing Forestry University, Beijing 100083, China. ²College of Biological Sciences & Biotechnology, Beijing Forestry University, Beijing 100083, China. ³Department of Botany and Plant Sciences, Institute of Integrative Genome Biology, University of California, Riverside, CA 92521, USA. ⁴Department of Horticulture and Landscape Architecture, Purdue University, West Lafayette, IN 47907, USA. ⁵Institute of Plant Stress Biology, State Key Laboratory of Cotton Biology, Department of Biology, Henan University, Jinming Street, Kaifeng 475001, China.

*These authors contributed equally to this work

‡Author for correspondence (linjx@bjfu.edu.cn)

© J.L., 0000-0002-1748-3083

These multifaceted approaches support the hypothesis that sterol-associated endocytic pathways are essential for the flg22-induced dynamics of FLS2 and plant defense.

RESULTS AND DISCUSSION

The sterol-deficient mutant *smt1* exhibits defects in flg22-induced plant immunity

Plant sterols are key components of membrane microdomains and are connected with defense responses (Kopischke et al., 2013). Interestingly, we found that treatment with the sterol-extracting reagent methyl- β -cyclodextrin (M β CD) increased flg22-induced ROS production (Fig. S1). To further examine the role of sterols in plant immune pathways, we analyzed the flg22-induced immune response in the sterol biosynthesis mutant *sterol methyltransferase 1* (*smt1*) (Diener et al., 2000). SMT1 is a C-24 methyltransferase that catalyzes the first step of sterol biosynthesis, the conversion of cycloartenol to 24-methylenecycloartenol, and the *smt1* mutant has defects in sterol composition (Diener et al., 2000; Clouse, 2002). As shown in Fig. 1A,B, ROS rapidly accumulated in wild-type plants treated with flg22. However, in the *smt1* mutants, flg22-induced ROS production was significantly higher (up to 40%) compared with the wild type.

To confirm whether the increased ROS production was due to increased expression of *FLS2* in the *smt1* mutants, we performed quantitative reverse transcription PCR (qRT-PCR) to measure *FLS2* expression. We observed no significant difference in *FLS2* mRNA

levels between the wild-type and the *smt1* mutant plants (Fig. 1C). Furthermore, immunoblot analysis showed that the FLS2 protein levels were comparable in the wild type and the *smt1* mutant lines (Fig. 1D), indicating that the steady-state levels of the FLS2 receptor likely cannot account for the observed increase in flg22-induced ROS production in the *smt1* mutants, and that sterols affect the flg22-induced ROS burst.

Therefore, we subsequently investigated the role of sterols in flg22-induced plant immunity. By investigating flg22-induced calcium influx, one of the earliest signaling events that occurs within 2-5 min after PAMP perception (Smith et al., 2014), we found that the *smt1* mutants exhibited a rapid and strong increase in $[Ca^{2+}]_{cyt}$ when compared with the wild-type plants (Fig. 1E,F), suggesting that, compared with wild type, the *smt1* mutants were more sensitive to the flg22 treatment.

MAP kinases (MAPKs) also play important roles in plant defenses and we next examined flg22-induced MAPK activity in the *smt1* mutants. *CYP81* and *WRKY40* are MAPK-dependent marker genes (Mao et al., 2011; Boudsocq et al., 2010). We found that the increases of *CYP81* and *WRKY40* transcript levels induced by treatment with flg22 were significantly lower in the *smt1* mutants when compared with the wild-type plants 30 min after treatment (Fig. 1G). We further monitored MAPK activation by measuring MPK phosphorylation in response to flg22 treatment. As shown in Fig. S2, the phosphorylation levels of MPK3, MPK4 and MPK6 were significantly lower in the *smt1* mutants than in wild type,

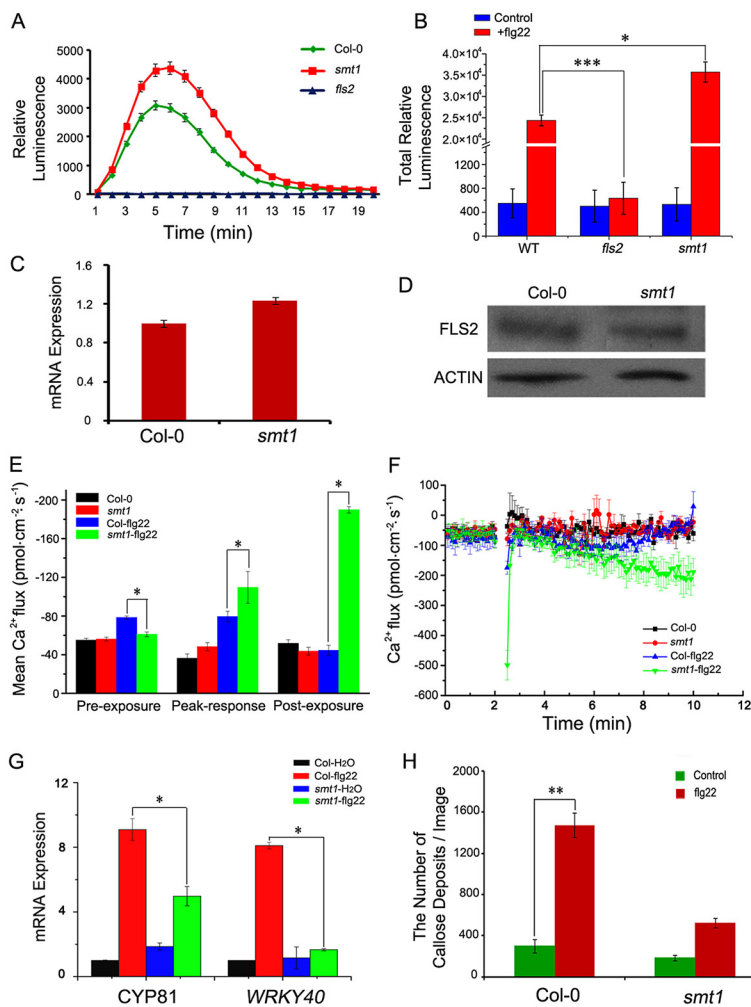


Fig. 1. The flg22-induced defense response is impaired in the sterol-deficient *smt1* mutant. (A) Reactive oxygen species (ROS) burst in response to flg22 measured as relative luminescence from a luminol-based assay at different times after flg22 treatment.

Experiments were repeated independently at least twice, with similar results. (B) Total ROS production (as RLU) in Col-0, *fls2* and *smt1* are shown before and after flg22 treatment in 16 rosette leaf disks. The experiment was performed twice with consistent results. For the ROS burst (A,B), relative amounts of H₂O₂ (expressed as relative luminescence) were measured immediately. Experiments were repeated independently at least twice, with similar results. Values are mean \pm s.d. ($n=8$). Statistical significance was determined using Student's *t*-test ($*P<0.05$ and $***P<0.001$). (C) The expression of *FLS2* by quantitative real-time PCR (qRT-PCR) with *ACTIN* as the reference gene. mRNA levels of *FLS2* were not significantly different between *smt1* and Col-0. Experiments were repeated independently at least twice, with similar results. Error bars represent the s.d.

(D) Protein levels of FLS2 measured by immunoblot analysis of *Arabidopsis* plant. (E) The mean Ca²⁺ fluxes of Col-0 and *smt1* before exposure to flg22, in response to flg22 and after exposure to flg22. Error bars represent the s.d. Statistical significance was determined using Student's *t*-test ($*P<0.05$). (F) The flg22-induced Ca²⁺ flux in Col-0 and *smt1*. A continuous Ca²⁺ flux recording of 10 min was conducted for each cell in test media. Each point represents the mean for 8-10 individual plants \pm s.e.m. (G) mRNA levels of *CYP81* and *WRKY40* were significantly different between Col-0 and *smt1* 30 min after mock treatment or treatment with 10 μ M flg22. For qRT-PCR, 10-day-old *Arabidopsis* Col-0 were treated with flg22 for 30 min. Experiments were repeated independently at least twice, with similar results. Error bars represent the s.d. Statistical significance was determined using Student's *t*-test ($*P<0.05$).

(H) Quantification of Aniline Blue-stained callose deposits in Col-0 and *smt1* without and with 2 μ M flg22 treatment (untreated, $n=9$ images; flg22 treated, $n=12$ images). Error bars represent the s.d. Statistical significance was determined using Student's *t*-test ($**P<0.01$).

consistent with the qRT-PCR results measuring *CYP81* and *WRKY40* expression (Fig. 1G).

Other studies have examined the effect of brassinosteroids on *smt1* plants (Diener et al., 2000). The root growth of *smt1* mutants is extremely sensitive to epibrassinolide (eBL) treatment (Diener et al., 2000) and eBL can suppress flg22-mediated immunity responses (Belkhadir et al., 2012; Albrecht et al., 2012). However, in *smt1* plants, reduced endogenous brassinolide biosynthesis caused by introducing the brassinosteroid-deficient mutant *deetiolated2* (*det2*) into the *smt1* background did not rescue the poor growth of *smt1* roots (Diener et al., 2000; Carland et al., 2010), suggesting that the phenotypic abnormalities of *smt1* are not due to the accumulation of brassinolides. Therefore, we inferred that the immune defects after flg22 treatment resulted mainly from the altered sterol biosynthesis in *smt1* mutants.

To further investigate the role of sterols in flg22-induced defenses, we examined callose deposition, another important marker of PAMP-mediated immunity. The flg22-induced callose deposition was significantly impaired in the *smt1* mutants when compared with the wild type 24 h post-infiltration of active flg22 (Fig. 1H and Fig. S3), although no difference was detected in the plants infiltrated with H₂O (Fig. 1H and Fig. S3). These analyses of the *smt1* mutants indicate that sterols play a profound role in flg22-induced plant immunity. Consistent with this, accumulating evidence shows that plant immunity is achieved by the formation of nanometer-scale membrane domains (termed microdomains), which act as signaling hubs (Keinath et al., 2010; Stanislas et al., 2009) and sterols are the main lipid components of these membrane microdomains.

FLS2 shows different dynamics at the plasma membrane in the sterol-deficient *smt1* mutants

Membrane-localized receptors sense environmental cues that trigger a physiological response (Li et al., 2013). The flg22 receptor FLS2 is a well-studied leucine-rich repeat receptor in plant immunity, and is used for studies of receptor-mediated immunity in plants (Yeh et al., 2015). Although previous studies have addressed flg22-induced defense responses (Ben Khaled et al., 2015), the dynamic behavior of FLS2 in the plasma membrane remains largely unknown.

Precise analyses with high spatial and temporal accuracy are required to characterize the dynamics of membrane receptors; e.g. VA-TIRFM and single-particle tracking of fluorescent proteins can be used to image membrane proteins and measure their dynamic movements. To probe the dynamics of FLS2 in the membrane, we therefore generated transgenic *Arabidopsis* plants expressing *FLS2* fused with *GFP* under the control of the native *FLS2* promoter in the *fls2* mutant. Immunoblot analysis showed that the FLS2-GFP fusion was expressed (Fig. S4A) and *FLS2-GFP* fully rescued the ROS production (Fig. S4B) and callose deposition defects of the *fls2* mutant (Fig. S4C), indicating that FLS2-GFP is functional. We next used VA-TIRFM to image FLS2-GFP in living leaf epidermal cells. The FLS2-GFP fluorescent signal appeared as discrete spots at the plasma membrane (Fig. 2A,B) and we applied VA-TIRFM to analyze the dynamics of these spots (Wang et al., 2018). We found that numerous FLS2-GFP fluorescent spots disappeared from or came into the focal plane during live-cell imaging (Fig. 2C,D and Movie 1), indicating exocytosis or endocytosis of plasma membrane components. Single-particle tracking analysis of the time series of images revealed that FLS2 is highly mobile and heterogeneously distributed at the plasma membrane.

Sterols are integral components of the cell membrane and affect the lateral mobility of plasma membrane proteins (Saka et al., 2014). To study the effect of sterols on the diffusion of FLS2-GFP, we measured the range of motion of FLS2-GFP in the *smt1* mutants. Under control conditions, the motion range of FLS2 showed a bimodal distribution: long-distance motion (67.8%, $3.05 \pm 0.41 \mu\text{m}$, the Gaussian peak value) and short-distance motion (32.2%, $1.73 \pm 0.13 \mu\text{m}$, the Gaussian peak value) (Fig. 2E,I). Upon flg22 treatment, the percentage of FLS2-GFP exhibiting short-distance motion decreased to 20.6% and those exhibiting long-distance motion increased to 79.4% compared with the control (Fig. 2E,I and Movie 2), indicating that flg22 treatment activated long-distance FLS2-GFP movement.

In the *smt1* mutants carrying *FLS2-GFP*, long-distance and short-distance motion accounted for 63.2% and 36.8% (Fig. 2F,I and Movie 3), respectively, indicating that the sterol defect in the mutants slightly affected the range of FLS2-GFP motion. Moreover, under flg22 treatment, the percentage of long-distance and short-distance motion of FLS2-GFP accounted for 73.1% and 26.9% in *smt1* mutants, which was significantly different from the distribution in wild-type Col-0, implying that the *smt1* mutation affects the motion range of flg22-activated FLS2-GFP (Fig. 2F,I). This finding was confirmed by treatment with M β CD, which decreased the percentage of long-distance motion of flg22-activated FLS2 (Fig. S5A,B and Movie 4), suggesting that reduction of the amounts of sterols significantly affected the range of motion of flg22-activated FLS2-GFP.

We further plotted the distribution of diffusion coefficients of FLS2-GFP on histograms and fitted the histogram using the Gaussian function, in which we defined the Gaussian peaks (noted as \hat{G}) as the characteristic values. In the control, the \hat{G} values were $7.9 \times 10^{-3} \mu\text{m}^2/\text{s}$ (s.e. 7.72 to $8.18 \times 10^{-3} \mu\text{m}^2/\text{s}$) (Fig. 2G,J). In response to the flg22 treatment, the \hat{G} values were $1.48 \times 10^{-2} \mu\text{m}^2/\text{s}$ (s.e. 1.44 to $1.51 \times 10^{-2} \mu\text{m}^2/\text{s}$) (Fig. 2G,J and Movie 2), representing a marked increase in diffusion compared with the control plant. To further confirm that the effect was specific to flg22, we used flg22 Δ 2, a flg22-derived peptide lacking agonist activity (Danna et al., 2011). When the seedlings were treated with flg22 Δ 2, no significant effect was observed on the range of motion and diffusion coefficients of FLS2-GFP when compared with the control untreated plant (Fig. 2I,J). In the *smt1* mutants, there was a slight but not significant increase in the diffusion coefficient (from $7.9 \times 10^{-3} \mu\text{m}^2/\text{s}$ to $8.85 \times 10^{-3} \mu\text{m}^2/\text{s}$) of FLS2-GFP when compared with that in Col-0 without flg22 treatment (Fig. 2H,J and Movie 3). Notably, the diffusion coefficient was $1.07 \times 10^{-2} \mu\text{m}^2/\text{s}$ in *smt1* mutants under flg22 treatment, significantly lower than that in Col-0 under flg22 treatment (Fig. 2H,J). A similar result was observed when the plants were treated with M β CD (Fig. S5C,D and Movie 4), supporting the idea that depletion of sterols significantly affects the dynamic behavior of flg22-activated FLS2.

A previous study showed that flg22 perception initiates the innate immune response (Li, et al., 2014). In addition, sterol-rich domains may modulate the dynamics and activity of some membrane proteins (Wang et al., 2015; Xue et al., 2018), which are involved in PAMP-induced immunity signaling (Keinath et al., 2010). In the present investigation, we showed that flg22-activated FLS2-GFP spots move faster and diffuse into wider regions in comparison with inactivated FLS2-GFP, indicating that the dynamic behaviors of FLS2 were closely related to flg22-induced signaling. Moreover, disruption of sterols by M β CD treatment or in *smt1* mutants significantly affected flg22-induced plant immunity (Fig. 1) and the diffusion of FLS2-GFP (Fig. 2I,J). Therefore, we concluded that

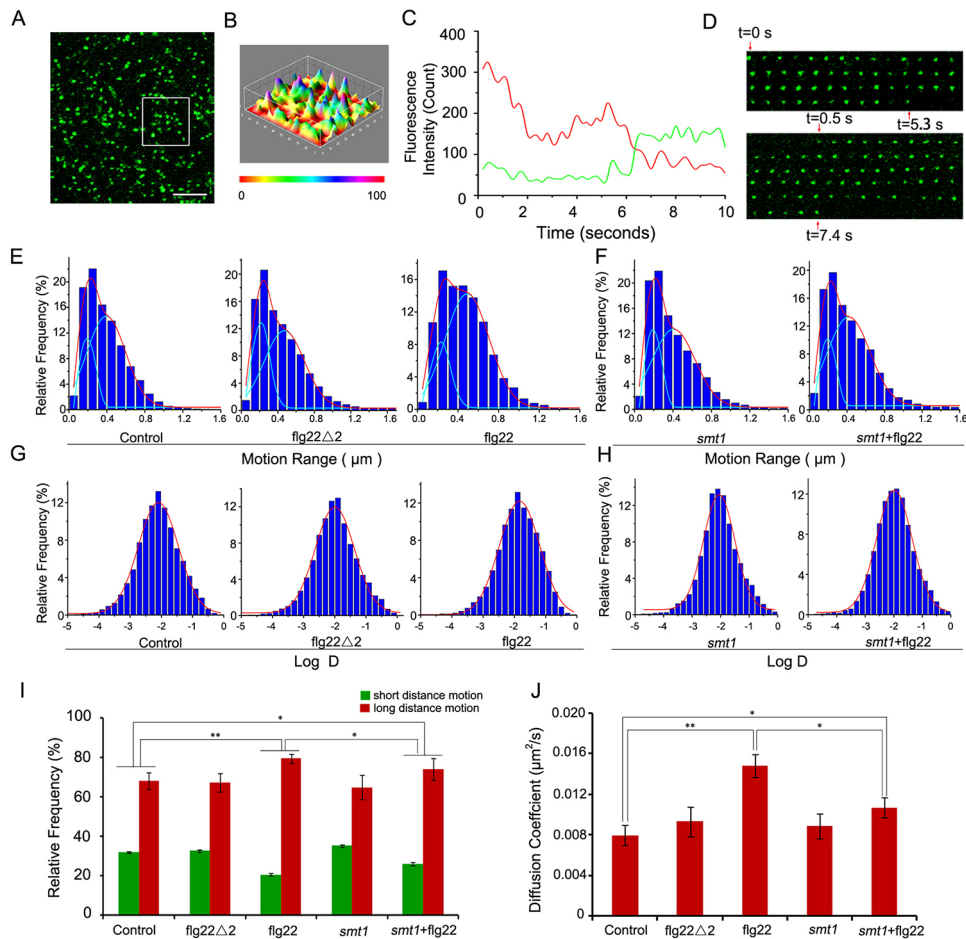


Fig. 2. Effects of sterols on the dynamics of FLS2-GFP spots at the plasma membrane. (A) A typical single-particle image of FLS2-GFP at the plasma membrane of living cells. Scale bar: 5 μ m. (B) Three-dimensional luminescence plots of the FLS2-GFP spots in A, showing varied fluorescence intensity among different spots. (C) Fluorescence intensity tracks of single FLS2-GFP particles showing their disappearance and appearance. (D) FLS2-GFP spots appeared at a different time, stayed for a short or longer time, then disappeared. (E) Distribution of FLS2-GFP motion range under control ($n=7382$ spots), flg22 $\Delta 2$ (a flg22-derived peptide lacking the agonist activity of flg22) (15 min) ($n=9753$ spots) and flg22 (15 min) ($n=11,072$ spots) treatment. (F) Distribution of FLS2-GFP motion range in *smt1* mutant seedlings ($n=8970$ spots) and in *smt1* mutant seedlings after flg22 (15 min) ($n=12,331$ spots) treatment. (G) Distribution of FLS2-GFP diffusion coefficients under control ($n=7787$ spots), flg22 $\Delta 2$ (15 min) ($n=12,694$ spots) and flg22 (15 min) ($n=11,073$ spots) treatment. (H) Distribution of FLS2-GFP diffusion coefficients in *smt1* mutant seedlings ($n=6511$ spots) and in *smt1* mutant seedlings after flg22 (15 min) ($n=13,357$ spots) treatment. (I) Frequency of long-distance and short-distance motions for FLS2-GFP under different environment. Error bars represent the s.d. Statistical significance was determined using Student's *t*-test ($*P<0.05$ and $**P<0.01$). (J) Diffusion coefficients of FLS2-GFP under different environments. Error bars represent the s.d. Statistical significance was determined using Student's *t*-test ($*P<0.05$ and $**P<0.01$).

sterols are involved in the flg22-induced immune responses, acting by regulating FLS2 motions.

Sterols change FLS2-GFP dwell times at the plasma membrane

Previous studies have shown that the binding of signaling molecules to activated receptors resulted in receptor endocytosis (Schlessinger, 2002). Single-particle tracking provides a powerful method with which to study membrane protein state and local environment, which can constrain protein dwell time (Flores-Otero et al., 2014; Hao et al., 2014). As flg22-activated FLS2 receptors can internalize into endosomes, we attempted to investigate whether sterols affect the dwell time of FLS2 at the plasma membrane. Therefore, we used VA-TIRFM to investigate the change in dwell time of FLS2 particles in response to flg22 treatment. When the frequency distribution of the FLS2-GFP dwell times under the different treatments was fitted to an exponential function, we found that flg22 treatment led to significantly shorter dwell times ($\tau=1.24$ s) than that

in the control seedlings ($\tau=2.15$ s) (Fig. 3A-D,I). However, M β CD treatment ($\tau=2.73$ s) resulted in longer dwell times than that of the control seedlings (Fig. 3E,F,I), whereas the dwell times of FLS2 became longer in the cells treated with M β CD together with flg22 ($\tau=1.91$ s) when compared with flg22 treatment (Fig. 3G,H,I). From the different dwell times of FLS2 at the plasma membrane in the various treatments, we speculated that the internalization of FLS2 into endosomes is a highly efficient way to control FLS2 activity and FLS2 endocytosis may occur through more than one endocytic pathway.

Sterols affect FLS2 clustering rather than changing the homo-oligomeric state of FLS2

The lateral mobility of many membrane receptor proteins depends on their oligomerization status (Low-Nam et al., 2011). Activation of membrane receptor proteins generally involves ligand-induced homo/heterodimerization or hetero-oligomerization in membrane microdomains and leads to signal transduction

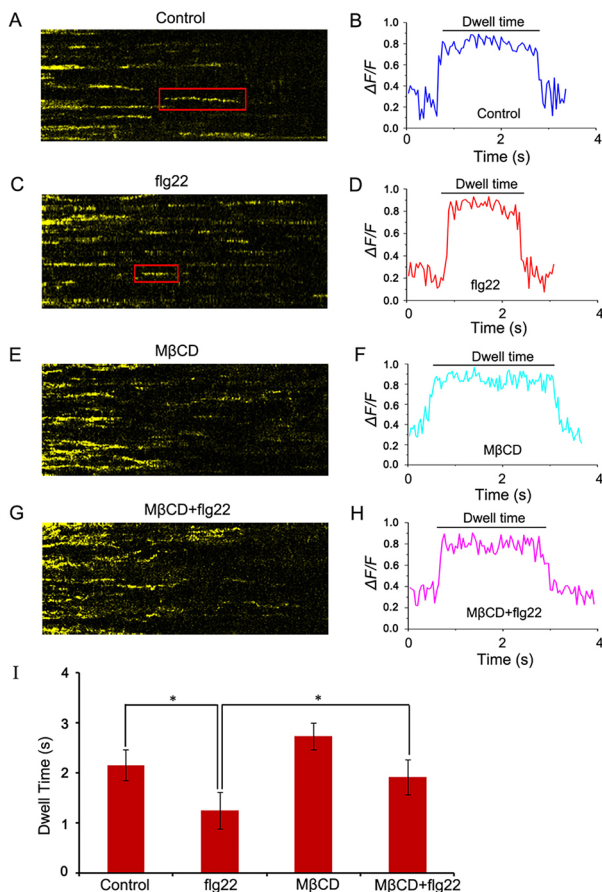


Fig. 3. Different environments induce specific dwell times of the FLS2.

(A,C,E,G) Representative kymographs showing individual FLS2-GFP dwell times in the presence of the control (A), flg22 (C) and M β CD (E) treatment, and M β CD and flg22 co-treatment (G). (B,D,F,H) Representative traces of normalized fluorescence from the control (B), flg22 (D) and M β CD (F) treatment, and M β CD and flg22 co-treatment (H). (I) Dwell times were analyzed under control, flg22 and M β CD treatment, and under M β CD and flg22 co-treatment. Error bars represent the s.d. Statistical significance was determined Student's *t*-test (**P*<0.05).

(Schlessinger, 2002; Corriden et al., 2014). In a previous study, fluorescence resonance energy transfer (FRET) and bimolecular fluorescence complementation (BiFC) assays showed that FLS2 does not undergo homodimerization either before or after flg22 treatment in *Arabidopsis* protoplasts (Ali et al., 2007), consistent with protein crystal structure studies (Sun et al., 2013). In the present study, by analyzing sequential images, we found that two FLS2 fluorescence spots diffused laterally along the membrane, collided and then fused together (Fig. 4A). By examining photobleaching steps, which reflect the oligomerization status of the target proteins (Ulbrich and Isacoff, 2007; Das et al., 2007), we found that most of the FLS2-GFP molecules exhibited one-step bleaching, and a few exhibited two-step bleaching (Fig. 4B,C) indicating that FLS2 at the plasma membrane of living cells exists in multiple oligomeric forms, including monomers and dimers.

To clarify whether FLS2 exists as dimers, we carried out luciferase complementation assays in *Nicotiana benthamiana* plants, with FLS2-Nluc and the non-interacting protein Cluc-CONSTITUTIVE PATHOGEN RESPONSE 5 (CPR5) as a negative control and FLS2-Cluc plus BIK1-Nluc as a positive control. The results showed that FLS2 can interact with itself and

BIK1 but not with CPR5 in the absence or in presence of flg22 (Fig. 4D). To further verify the dimerization of FLS2, we performed co-immunoprecipitation assays in *Arabidopsis* protoplasts. For this purpose, FLS2-HA/FLS2-FLAG and FLS2-HA/BAK1-FLAG were co-transfected into *Arabidopsis* protoplasts. As shown in Fig. 4E, FLS2-HA was detected in the FLS2-FLAG immune complex using anti-HA antibodies both in the absence and presence of flg22 (Fig. 4E), demonstrating that FLS2 can form a homo-dimer either in the inactive or active state.

We next addressed whether FLS2 was predominantly present as a monomer or dimer. Using progressive idealization and filtering (PIF) algorithms, we found that the ratios of the monomer versus the dimer of FLS2-GFP in an inactive state (0.86:0.14) were similar to the ratios in the active state (0.84:0.16) (Fig. 4F), indicating that monomers are the predominant species. In addition, dimers were detected before and after flg22 treatment. Moreover, with the M β CD treatment, the ratio of the monomer versus the dimer was comparable with that in the control (Fig. 4F), suggesting that sterols do not affect the homo-oligomeric state of FLS2.

Receptor-ligand binding can induce conformational changes of the receptor ectodomain, which result in receptor dimerization and receptor oligomerization or clustering (Clayton et al., 2005). With VA-TIRFM, we observed that most of the FLS2-GFP existed in low-oligomeric spots with an average size of $2.43 \times 2.43 \pm 0.92$ pixels and a fluorescence intensity of 6968.4 ± 697 counts/pixel in the control plants (Fig. 5A-C). Under flg22 treatment, the FLS2-GFP spots became larger and their fluorescence intensity became brighter when compared with those in the control plant (Fig. 5A). We found that the large spots exhibited exponential decay without discrete steps (Fig. 5D), suggesting that each large spot was a cluster of several FLS2-GFP molecules. The flg22-induced clusters exhibited an average size of $4.12 \times 4.12 \pm 1.77$ pixels and a fluorescence intensity of $12,254.5 \pm 1505$ counts/pixel after 30 min (Fig. 5B,C). When treated with M β CD coupled to flg22, the average size and fluorescence intensity of FLS2-GFP spots significantly decreased to $2.83 \times 2.83 \pm 0.96$ pixels and 8649.5 ± 1291 counts/pixel (Fig. 5B,C), suggesting that the M β CD treatment resulted in a reduction of flg22-induced FLS2-GFP clusters at the plasma membrane (Fig. S6).

Consistent with previous studies (Gao et al., 2015; Wang et al., 2015), Zipfel and colleagues found that cluster formation relies on the integrity of the plasma membrane, as M β CD-induced sterol depletion of the plasma membrane destroys clustering (Bücherl et al., 2017). Furthermore, clustering is required for kinase activity, and abnormal protein complex organization can affect the internalization of membrane proteins (de Heus et al., 2013). Therefore, our findings suggest that sterols are involved in modulating FLS2 signal transduction by adjusting the clustering of FLS2 induced by flg22 at the plasma membrane.

The flg22-triggered FLS2 internalized partially through CME

Clustering can promote endocytosis of plasma membrane proteins and this regulates signaling of the receptor (Hofman et al., 2010). FLS2-GFP translocation from the plasma membrane to endosomes is mainly mediated by clathrin (Ben Khaled et al., 2015; Mbengue et al., 2016). We applied fluorescence correlation spectroscopy (FCS) to precisely measure the density of FLS2 molecules under different conditions. FCS is a powerful technique for analyzing particle concentrations, mobilities and diffusion at the single-particle level, and has been successfully applied in plants (Li et al., 2011). Our FCS analyses showed that the density of FLS2 molecules at the plasma membrane significantly increased after

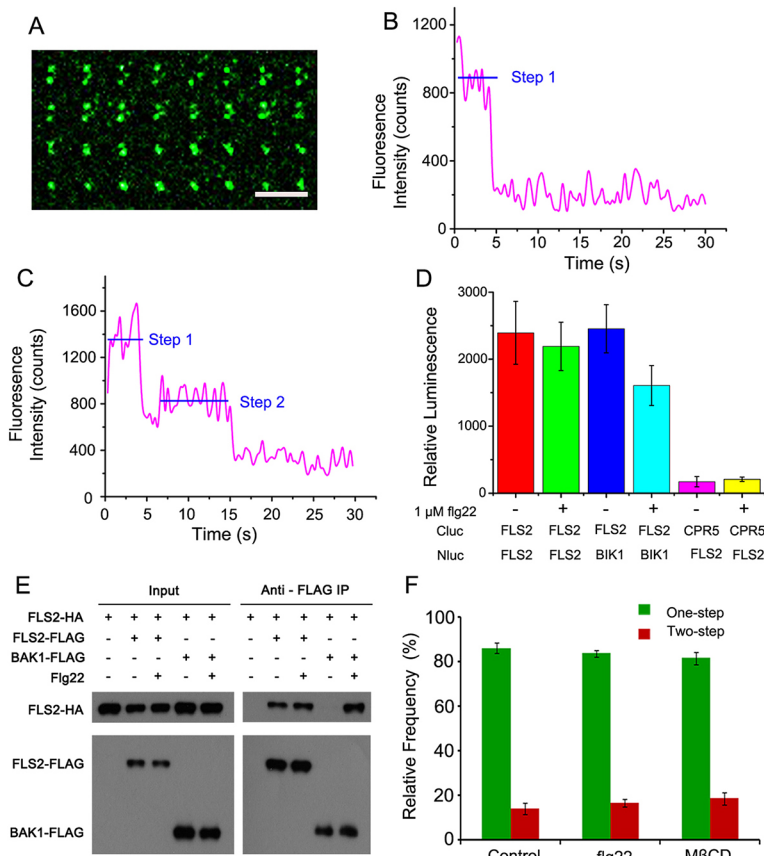


Fig. 4. FLS2 aggregation status. (A) Series of images from single-particle live-cell imaging showing two FLS2-GFP spots merging. Scale bar: 5 μ m. (B) Time course of GFP emission after background correction showing one-step bleaching. (C) Time course of GFP emission after background correction showing two-step bleaching. (D) FLS2 aggregation status using split-luciferase assays in *N. benthamiana*. Split-luciferase assays were conducted in the presence or absence of flg22. Co-expression of Cluc-CPR5 and FLS2-Nluc was used as a negative control, while co-expression of FLS2-Cluc and BIK1-Nluc served as a positive control. Experiments were repeated independently at least twice with similar results. +, applied flg22 treatment; -, no peptide treatment. Values represent mean relative luminescence units (RLU) \pm s.d. ($n=8$). (E) The interaction between FLS2 and FLS2 was confirmed by co-immunoprecipitation assays in *Arabidopsis* protoplasts. The FLS2-HA construct was co-expressed with FLS2-FLAG or BAK1-FLAG in *Arabidopsis* protoplasts. FLS2-HA was present in the FLS2-FLAG immune complex before and after flg22 treatment. Furthermore, using FLS2-HA plus BAK1-FLAG as a positive control, the FLS2-HA only appeared in the flg22-induced BAK1-FLAG complex. In contrast, using FLS2-HA as a negative control, FLS2-HA did not appear in the FLAG complex either before and after flg22 treatment. +, applied flg22 treatment; -, no peptide treatment. The experiment was repeated three times and data from one representative experiment are shown. (F) Ratio of FLS2 monomer and dimer before ($n=428$ spots) and after ($n=435$ spots) flg22 treatment. Error bars represent s.d.

treatment with Tyrphostin A23 (TyrA23), which is an inhibitor of the clathrin-mediated endocytosis pathway (Fig. 6A). Similar results were found in equivalent experiments using immunoblot assays (Fig. 6B). In addition, using single particle tracking analysis, we found that the flg22-induced diffusion of FLS2-GFP was significantly impaired in the *clathrin light chain2* (*clc2*) and *clc3* double mutants (*clc2-1 clc3-1*) or using TyrA23 treatment when

compared with the control plant (Fig. S7), supporting the notion that clathrin is involved in the internalization of FLS2, as reported previously (Mbengue et al., 2016; Ortiz-Morea et al., 2016).

Moreover, our experiments show that TyrA23 treatment significantly blocked the constitutive endocytosis of FLS2-GFP accumulated in brefeldin A (BFA) compartments (Fig. 6C), in seedlings treated with BFA. BFA is an inhibitor of vesicle recycling

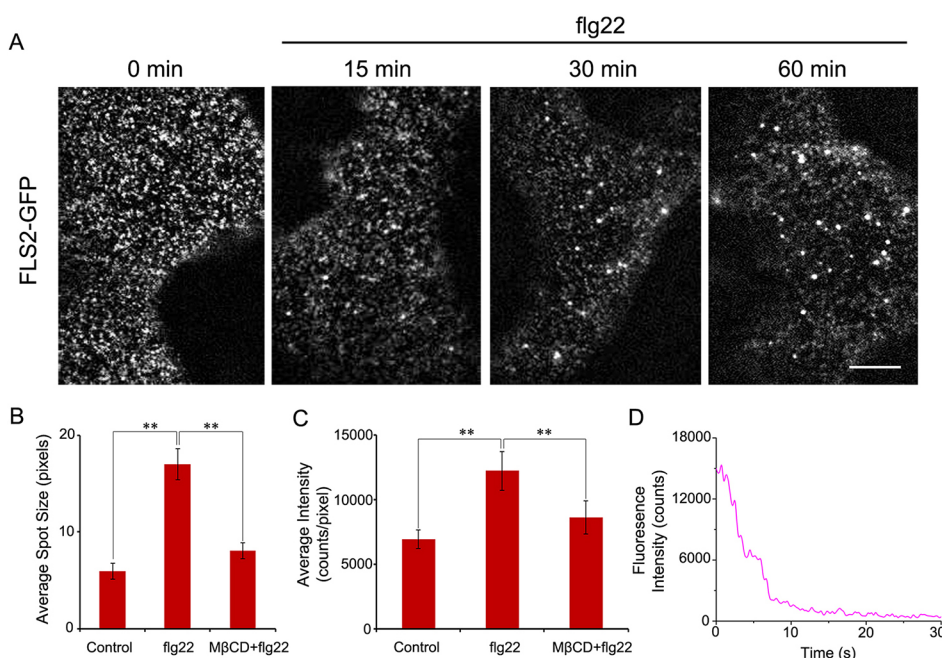


Fig. 5. The flg22-induced FLS2-GFP forms receptor clusters in a time-dependent manner at the plasma membrane. (A) Typical images showing diffraction-limited fluorescent spots of FLS2-GFP on the fixed cell membrane of *Arabidopsis* leaf epidermis cells with flg22 treatment for 15, 30 and 60 min, imaged using TIRFM. The image is a section of the first frame of a stack of images with the background subtracted. Scale bar: 1 μ m. (B,C) Average size (B) and fluorescence intensity (C) of FLS2-GFP fluorescent spots under control ($n=178$) and flg22 treatment ($n=239$), and M β CD and flg22 co-treatment ($n=247$), showing that flg22 induced the massing of FLS2-GFP oligomers into clusters. Error bars represent the s.d. Statistical significance was determined using Student's *t*-test (** $P<0.01$). (D) Representative time course of FLS2-GFP spots under flg22 treatment in *Arabidopsis* leaf cells, showing the approximately exponential distribution of the bleaching steps.

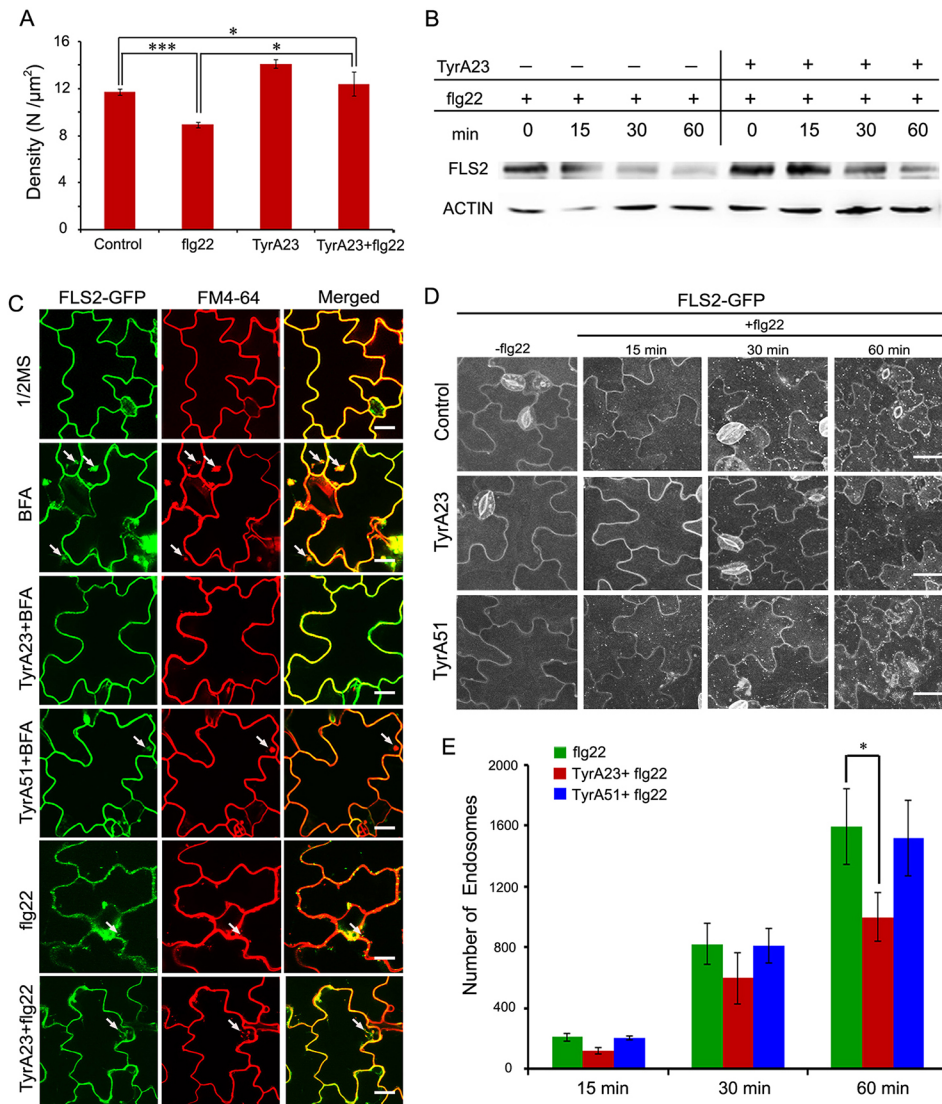


Fig. 6. TyrA23 affects the internalization of FLS2-GFP. (A) The density of FLS2-GFP particles in the different treatments was measured by FCS ($n=30$ cells from five seedlings for each treatment). Error bars represent the s.d. Statistical significance was determined using Student's t -test ($*P<0.05$ and $***P<0.001$). (B) Immunoblot analysis of FLS2 protein levels under flg22, flg22 and TyrA23 co-treatment for 15, 30 and 60 min. (C) FLS2-GFP subcellular localization in the presence of the indicated chemical inhibitors and ligands. The left photographs represent GFP signal showing subcellular localization of FLS2-GFP in the presence of the indicated chemicals and ligands. The middle photographs represent red fluorescence signal showing the plasma membrane stained by FM4-64. The right photographs represent the merge of FLS2-GFP and FM4-64 staining. Arrows indicate BFA bodies and FLS2 endosomes ($n=15$ cells from five seedlings for each treatment). Scale bar: 10 μ m. (D) Confocal image of *Arabidopsis* leaf epidermis with FLS2-GFP treated with flg22, with TyrA23 and flg22, and with TyrA51 and flg22 for 15, 30 and 60 min. Scale bar: 20 μ m. (E) Quantitative analysis of FLS2-GFP endosomal spots per image in response to flg22 treatment over time. $n=3$ seedlings for each treatment. Error bars represent the s.d. Statistical significance was determined using Student's t -test ($*P<0.05$).

in plants, acting through inhibition of ADP ribosylation factor-guanine exchange factors (Grebe et al., 2003; Naramoto et al., 2010). Quantitative analyses revealed the internalization of flg22-induced FLS2-GFP was not fully blocked (reduced by about 40%) after TyrA23 pretreatment (Fig. 6D,E), which was consistent with the results in the *clc2-1 clc3-1* mutants (Fig. S8). As a control, we analyzed the endocytosis of FLS2-GFP using Tyrothostin A51 (TyrA51), the inactive analog of TyrA23 (Wang et al., 2015), and found that TyrA51 had no significant effects on the internalization of FLS2-GFP (Fig. 6C-E). In addition, we found when co-expressing FLS2-GFP with clathrin light chain (CLC)-mCherry or with VHA-a-RFP [the *trans-Golgi* network (TGN) markers], FLS2-GFP showed only partial colocalization with CLC-mCherry (17.0%) or VHA-a1-mCherry (14.7%) after 30 min of treatment with flg22 (Fig. 7A). Therefore, these results provided strong evidence that more than one endocytic pathway acts to coordinate the endocytosis of FLS2.

Endocytosis of activated FLS2 is dependent on sterols

Previous reports showed that sterol-enriched domains may play a role in pathogen-associated molecular pattern-induced signaling and affect the endocytosis of plasma membrane proteins in plants (Keinath et al., 2010; Yadeta et al., 2013; Malinsky et al., 2013). In

plants, the membrane microdomain-associated endocytic pathway has also been described, and includes microdomain-localized proteins such as flotillins (Li et al., 2012). Yu et al. showed that flg22 can increase the endocytosis of GFP-Flot1 (Yu et al., 2017). Surprisingly, we found that FLS2-GFP showed a significant colocalization with AtFlot1-mCherry (marker of sterol-rich domains) endosomes (44.9%) (Fig. 7A). Given the link between membrane microdomains and endocytosis, this finding indicates that sterols may be involved in FLS2 internalization.

To test this hypothesis, we analyzed the degree of colocalization of FLS2-GFP with AtFlot1-mCherry and CLC-mCherry by calculating protein proximity indexes (PPI) (Fig. 7B,C) (Zinchuk et al., 2011). We measured the PPI values before and after flg22 treatment. The results showed that the mean FLS2-to-Flot1 PPI showed a highly significant increase (from 27.2% to 44.8%) in response to flg22. The FLS2-to-CLC PPI also increased significantly (from 48.3% to 60.5%) after 30 min of flg22 treatment (Fig. 7D), confirming that microdomains are recruited for flg22-dependent FLS2 endosomes.

To test whether sterols affect the internalization of proteins, we applied BFA to inhibit endocytic recycling (Naramoto et al., 2010). FLS2-GFP did not accumulate in BFA compartments in cells treated with M β CD and BFA when compared with BFA alone (Fig. S9).

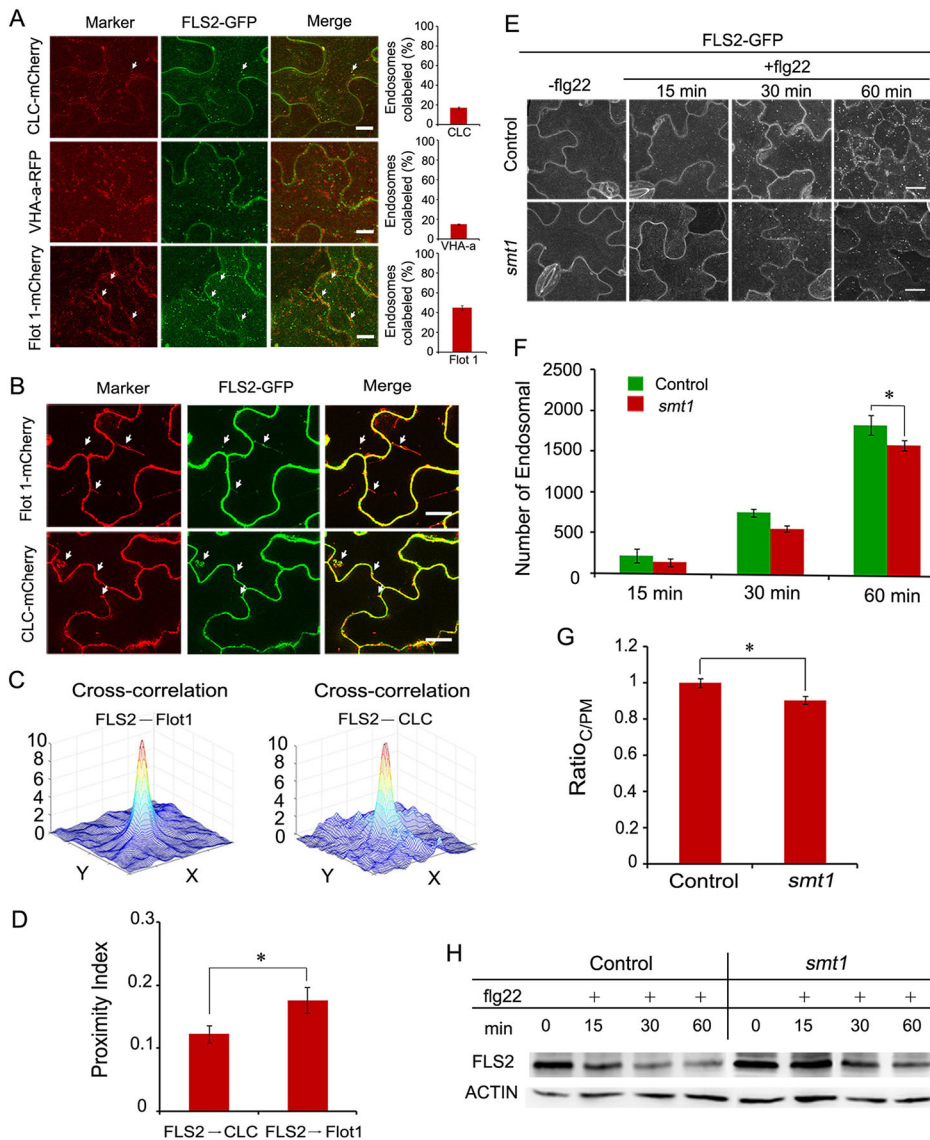


Fig. 7. Endocytosis of FLS2 is associated with sterols. (A) Colocalization of FLS2-GFP vesicles with the CLC-mCherry, VHA-a1-RFP and Flot 1-mCherry in crossed transgenic lines. Arrows indicate endosomes showing colocalization. $n=3$ seedlings for each treatment. Scale bars: 20 μm . (B) FLS2-GFP colocalized with Flot1/CLC-mCherry in crossed transgenic lines. Arrows indicate endosomes showing colocalization. $n=3$ seedlings for each treatment. Scale bars: 20 μm . (C) 3D plot of FLS2-GFP and Flot1/CLC-mCherry cross-correlation versus pixel shift. (D) Mean protein proximity indexes showing the FLS2-Flot1/CLC degree of proximity under flg22 treatment ($n=39$). Experiments were repeated independently at least twice, with similar results. Error bars represent the s.d. Statistical significance was determined using Student's *t*-test ($*P<0.05$). (E) *smt1* mutants. Confocal image of *Arabidopsis* leaf epidermis with FLS2-GFP treated with flg22 for 15, 30 and 60 min. Scale bars: 20 μm . (F) *smt1* mutants. Quantitative analysis of FLS2-GFP endosomal spots per image in response to flg22 treatment over time. $n=3$ seedlings for each treatment. Error bars represent the s.d. Statistical significance was determined using Student's *t*-test ($*P<0.05$). (G) Quantification of FLS2 endocytosis as estimated by the ratio of the average signal intensity in the cytosol over that at the PM ($n=54$). Experiments were repeated independently at least thrice, with similar results. Error bars represent the s.d. Statistical significance was determined using Student's *t*-test ($*P<0.05$). (H) Immunoblot analysis of FLS2 protein levels under flg22 treatment for 15, 30 and 60 min in control and *smt1* mutants.

Furthermore, the number of FLS2-GFP endosomes in the *smt1* mutants was notably lower than those in the control after 30 min of flg22 treatment, and this trend became more pronounced after 60 min of flg22 treatment (Fig. 7E,F), which was similar to the results with the M β CD treatment (Fig. S10A and B), indicating the existence of a close relationship between FLS2 localization and sterols. To exclude potential side effects of M β CD, we compensated for the loss of plasma membrane cholesterol by adding M β CD-cholesterol complexes (10 mM) to seedlings following M β CD treatment (Chadda et al., 2007). We found that the internalization of FLS2 recovered after sterol supplementation (Figs S9 and S10A,B), indicating the disturbance of FLS2 internalization resulted largely from the depletion of cholesterol, not from potential side effects of M β CD.

Using the relative intensity of cytoplasm/plasma membrane as a proxy for the internalization rate, we found that the ratio in the *smt1* mutants was reduced to 17% after flg22 treatment, which was significantly lower than that in the wild-type plant (27.8%) (Fig. 7G). Similar results were also found in the M β CD-pretreated plants (Fig. S10C), suggesting that FLS2 internalization was impaired in the *smt1* mutants.

In the present study, we precisely measured the density of FLS2-GFP on the membrane by FCS. The density of FLS2-GFP on plasma

membranes was 11.72 molecules mm^{-2} before flg22 treatment, and 8.93 molecules mm^{-2} after flg22 treatment (Fig. S11A). After treatment with M β CD or M β CD coupled to flg22, the abundance of FLS2 molecules at the plasma membrane significantly changed compared with controls (12.87 molecules mm^{-2} for M β CD and 10.47 molecules mm^{-2} for M β CD coupled with flg22) (Fig. S11A), indicating that the internalization of FLS2-GFP, especially the flg22-induced internalization, was partly disrupted by M β CD. Western blotting demonstrated that the *smt1* mutation can significantly reduce flg22-induced degradation of FLS2 protein compared with that in the wild type (Fig. 7H), and similar results were obtained under M β CD treatment (Fig. S11B). Sterols are associated with endocytosis (Stanislas et al., 2014; Ferrer et al., 2017). For example, Hao et al. revealed that sterol extraction by treatment with M β CD significantly disrupted NaCl-induced GFP-RbohD internalization (Hao et al., 2014). Furthermore, the sterol biosynthesis mutants *cyclopropylsterol isomerase 1-1 (cpi1-1)* and *sterol methyltransferase 1 (smt1)* impaired endocytosis of PIN2 protein (Men et al., 2008; Willemsen et al., 2003). Taken together, these results further support the hypothesis that sterols coordinate the internalization of FLS2.

Endocytosis plays key roles in regulating signaling initiation at the plasma membrane, where plants can sense the external stimuli

and signaling through cell surface receptor-like kinases (RLKs) (Barbieri et al., 2016; Irani and Russinova, 2009). Some RLKs (including BRI1, FLS2, EFR and PEPR1/2) have been reported to undertake receptor-mediated endocytosis following ligand perception (Irani et al., 2012; Mbengue et al., 2016; Ortiz-Morea et al., 2016). More importantly, several lines of evidence support the idea that the sterol-associated endocytosis is involved in RLK stability and endocytosis. For example, sterols are essential for the activation of BRI1 signaling and BRI1 internalization (Wang et al., 2015). Given that sterols are involved in the internalization and signal transduction of FLS2 after sensing flg22, we speculated that sterols exert a profound role in regulating RLK endocytosis, which controls receptor availability on the plasma membrane and fine-tunes the delivery of signals to diverse downstream effectors, ultimately regulating the cellular response to different types of signals.

MATERIALS AND METHODS

Plant materials

All mutants and transgenic lines used were in the *Arabidopsis thaliana* Col-0 background. *Arabidopsis* seeds were surface sterilized for 30 s in 85% ethanol/H₂O₂ and vernalized at 4°C for 1 day in the dark. Seedlings were then grown on half-strength Murashige and Skoog (MS) medium. The plants were grown at 22°C under fluorescent light at 70% relative humidity with 16 h light/8 h dark photoperiods, unless otherwise specified. The following mutant and transgenic *Arabidopsis* lines have been described previously: *fls2*, *smt1*, *clc2-1clc3-1*, clathrin light chain (CLC)-mCherry, Flot 1-mCherry and VHA-a1-RFP (Gómez-Gómez and Boller, 2000; Diener et al., 2000; Wang et al., 2013; Li et al., 2012; Mbengue et al., 2016). Dual-color lines expressing FLS2-GFP with CLC-mCherry, Flot1-mCherry and VHA-a-RFP were generated by crossing FLS2-GFP with CLC-mCherry, Flot1-mCherry and VHA-a-RFP, respectively.

Constructs

To generate the *FLS2* transgenic plants, a native *FLS2* promoter of 988 bp in length and the *FLS2* gene double myc-tag fusion were PCR amplified and cloned into pCambia2300. The *FLS2* promoter sequence was PCR amplified using the primers 5'-GGAATTCGAAGTTGTGAATTGTGATCATAGGA-3' (forward) and 5'-GGGGTACCGGTTTACACTTTAGAA-GAGTT-3' (reverse) carrying the *EcoRI* and *KpnI* sites. The coding sequence for *FLS2* (At5g46330) was PCR amplified using the primers 5'-GGGGTACCATGAAGTTACTCTCAAAGACCTTTTGTG-3' (forward) and 5'-ACGCGTCGACAACCTTCTCGATCCTCGTTACGATCT-3' (reverse) carrying the *KpnI* and *Sall* sites. Underlining indicates cleavage sites of restriction enzymes. The *FLS2* promoter and *FLS2* constructs were constructed by PCR-based cloning in vector pCambia2300. Desired *pFLS2:FLS2-2×myc-GFP* plasmids were introduced into the *fls2* mutant plants by *Agrobacterium*-mediated transformation.

Drug treatments

All chemicals were purchased from Sigma-Aldrich, if not otherwise indicated, and used at the following concentrations: TyrA23 (50 mM in DMSO, working solution 50 μM), TyrA51 (50 mM in DMSO, working solution 50 μM), methyl-β-cyclodextrin (MβCD) (200 mM in water, working solution 10 mM), brefeldin A (BFA) (50 mM in DMSO, working solution 50 μM) and FM4-64 (5 mM in DMSO, working solution 5 μM). The flagellin peptides flg22 and flg22Δ2 were synthesized by GL Biochem (Shanghai) and were used in a concentration of 10 μM (10 mM in double distilled H₂O). The TyrA23, TyrA51, MβCD and BFA treatments were performed as described previously (Wang et al., 2015) and stock solutions were diluted with 1/2 MS growth medium.

Microscopy

Arabidopsis seedlings were imaged with an Olympus FluoView 1000 inverted confocal microscope fitted with a 60× water-immersion objective

(numerical aperture 1). GFP/FM4-64 and RFP/mCherry were excited with 488 and 561 nm wavelengths, respectively, and the fluorescence emission spectra were detected at 500–530 nm for GFP, 600–700 nm for FM4-64 and 580–620 nm for RFP/mCherry. The original images were obtained from the same confocal microscope with the same laser and camera settings and then images were processed using the Olympus, Adobe Photoshop CS5 and ImageJ software packages.

TIRFM and single-particle fluorescence image analysis

Total internal reflection fluorescence microscopy (TIRFM) was performed on an inverted microscope with a total internal reflective fluorescence illuminator and a 100× oil-immersion objective (Olympus; numerical aperture=1.45). For the detection of FLS2-GFP particles at the plasma membrane, living leaf epidermal cells of 5-day-old seedlings were observed under VA-TIRFM. The images were acquired with 100 ms exposure times and time-lapse series images of single particles of FLS2-GFP were taken at up to 100 images per sequence. Proteins labeled with GFP or mCherry were excited with 473-nm or 561-nm laser lines, respectively, from a diode laser (Changchun New Industries Optoelectronics Tech. Co., Changchun, China) and their emission fluorescence was obtained with a filter (BA510IF for EGFP; HQ605/52 for mCherry). The fluorescent signals were acquired by a digital EMCCD camera (ANDOR iXon DV8897D-CS0-VP, Andor Technology, Belfast, UK) after filtering with two band-pass filters (525/545 and 609/654 nm). Images were acquired with 100 ms exposure times and stored directly on a computer. The methods used to analyze single-particle tracking were described previously (Wang et al., 2015).

A program named 'progressive idealization and filtering' (PIF) was used for the photobleaching step analysis. After background subtraction by the rolling ball method in ImageJ software, images were input into the PIF program and subjected to the steps described previously (McGuire et al., 2012).

FCS analysis

FCS was carried out on a Leica TCS SP5 FCS microscope equipped with a 488 nm argon laser, an in-house coupled correlator and an Avalanche photodiode. After acquiring images of cells in transmitted light mode, FCS was performed in the point-scanning mode. The diffusion of FLS2-GFP molecules into and out of the focal volume changed the local concentration of the fluorophore number, which led to spontaneous fluctuation of the fluorescence intensity. Finally, the FLS2-GFP density of individual cell membranes was calculated according to the protocol described previously (Li et al., 2011). Up to six random points were selected in one cell, five cells were chosen from a leaf and at least three representative leaves were measured for each study.

Quantification of cytoplasm and plasma membrane fluorescence

The images were obtained with a FluoView 1000 laser-scanning microscope (Olympus). The relative surface of the internalized proteins or relative fluorescence intensity at the plasma membrane was calculated with ImageJ software (National Institutes of Health, version 1.48) as previously described (Du et al., 2013).

Western blotting

Total proteins were extracted from 10-day-old seedlings of transgenic *FLS2-GFP* lines in the *fls2* or *smt1* mutant backgrounds under different conditions. The GFP antibody (Sigma-Aldrich) was raised against GFP peptides of FLS2-GFP protein. FLS2-GFP protein was denatured in buffer E [100 ml buffer E includes 1.5125 g Tris-HCl (pH 8.8), 11.1 ml glycerine, 1.2409 g Na₂S₂O₅, 5 mM DTT and 1 g SDS]. Proteins were separated with an 8% SDS-polyacrylamide gel and transferred to a nitrocellulose membrane. A 1:4000 dilution was used for the anti-GFP antibody.

Measurement of Net Flux of Ca²⁺

The net flux of Ca²⁺ was measured using the non-invasive micro-test technique (NMT) method, as previously described (Yan et al., 2015). This technique is used to study the flux of specific molecules from single cells

and/or tissues, and is also known as the self-referencing microelectrode technique. The Ca^{2+} electrode was fabricated as described by Yan et al., (2015). Pre-pulled and silanized glass micropipettes (2–4 μm aperture) were first filled with a backfilling solution (Ca^{2+} : 100 mM CaCl_2) to a length of about 1 cm from the tip. Then, the micropipettes were front-filled with selective liquid ion-exchange (LIX) cocktails to a column length of approximately 25 μm . The LIX cocktails were obtained from Sigma-Aldrich (Sun et al., 2009). An Ag/AgCl electrode holder was inserted from the back of the electrode until the tip contacted the surface of the electrolyte solution. DRIFEF-2 (World Precision Instruments) was used as a reference electrode. The electrodes were calibrated prior to the experiment in known calibration solutions (0.05, 0.1, and 0.5 mM Ca^{2+}). Only electrodes with Nernstian slopes between 53 and 62 mV/[log-C($\pm z$)] were used in our study (where z is the valence of the ion and C is the concentration of the ion).

Leaves from 7-day-old seedlings were fixed on the bottom of a 35 mm dish incubated in the test buffer. The Ca^{2+} flux of the leaves was then measured using NMT. Each plant was measured once. The leaves were then treated with 0.1 μM flg22 and the Ca^{2+} flux was measured again. The final flux values were reported as the mean of 7 to 11 individual leaves. The Ca^{2+} fluxes were calculated as described by Yan et al. (2015).

Quantitative reverse-transcription PCR

Total RNA was extracted from 10-day-old seedlings with a TiangenNApre Plant Kit (Tiangen) according to the manufacturer's instructions. Reverse transcription was performed using FastQuant RT Kit (Tiangen). qPCR was performed with the TiangenSurperRealPreMix Plus (SYBR Green). The flg22-induced early-response genes and primers were listed as follows: *WRKY40* (*Atlg80840*), 5'-GATCCACCGACAAGTGCTTT-3' and 5'-AGGGCTGATTGATCCCTCT-3'; *CYP81f2* (*At5g57220*), 5'-CTCATGCTCAGTATGATGC-3' and 5'-CTCCAATCTTCTCGTCTATC-3'.

Detection of callose deposition

Detection of callose deposition was performed as previously described (Cao et al., 2013). In brief, 7-day-old seedlings were infiltrated with 2 μM flg22 in six-well plates for 24 h. Control treatments were infiltrated with H_2O . Excised leaves were immediately cleared in 95% ethanol: H_2O (3:1) for at least 6 h. Subsequently, samples were rinsed with 50% ethanol and H_2O . Seedlings were stained with Aniline Blue in 0.15 M phosphate buffer (pH 9.5) and callose deposits were visualized using ultraviolet epifluorescence microscopy as described previously (Cao et al., 2013).

Oxidative burst measurement

ROS burst experiments were performed by a luminol-based assay as described previously (Sun et al., 2012). Leaves of 4-week-old transgenic *Arabidopsis* plants were sliced into 1 mm strips and incubated in 100 μl of H_2O in a 96-well plate overnight. The H_2O was then replaced by 100 μl of reaction solution containing 50 μM of luminol and 10 $\mu\text{g}/\text{ml}$ of horseradish peroxidase (Sigma-Aldrich) supplemented with 100 nM of flg22. Luminescence was acquired over time using a PhoteK camera and software. The reported data are pooled measurements from six independent leaves per condition originating from a minimum of three plants.

Co-immunoprecipitation assay

Protoplasts were isolated and transfected as previously described (Niu and Sheen, 2012). After incubation overnight, transformed protoplasts were treated with water or 1 mM flg22 for 10 min. Total protein was extracted with protein extraction buffer [50 mM HEPES (pH 7.5) 150 mM KCl, 1 mM EDTA, 0.2% Triton X-100, 1 mM DTT, proteinase inhibitor cocktail (Roche)]. For anti-FLAG IP, total protein was incubated with 50 μl agarose-conjugated anti-FLAG antibody (Sigma-Aldrich) for 4 h. After washing six times with extraction buffer. The bound protein was eluted by incubating with 3 \times FLAG peptide (Sigma-Aldrich) for 1 h. The immunoprecipitates were separated by SDS-PAGE and detected with immunoblotting.

Data analysis

The significance of arithmetic mean values for all data sets was assessed using Student's *t*-test. Error bars were calculated with the s.d. function in

Microsoft Excel. The differences at $P < 0.05$ were considered statistically significant. According to Student's *t*-test, characters in the figure represent statistically significant differences compared with control (* $P < 0.05$, ** $P < 0.01$ and *** $P < 0.001$).

Accession numbers

Sequence data used in this article can be found in the *Arabidopsis* Information Resource (TAIR) database under the following accession numbers: *FLS2* (AT5G46330), *Flot1* (AT5G25250) and *smt1* (At5g13710).

Acknowledgements

We sincerely thank Dingzhong Tang (University of Chinese Academy of Sciences) for providing the *fls2* mutant line and Timothy Nelson (Yale University) for providing the *smt1* mutant line. We also thank Qihua He (Peking University) for technical assistance with FCS.

Competing interests

The authors declare no competing or financial interests.

Author contributions

Methodology: L.F.; Software: Y.C., X.L., R.L., L.F., Y.Z.; Writing - original draft: Y.C., X.L., J.L.; Writing - review & editing: Y.C., X.L., M.Y., J.L.

Funding

This work is supported by the National Natural Science Foundation of China (31530084, 31622005, 31670182), and by the Beijing Advanced Innovation Center for Tree Breeding by Molecular Design, the Program of Introducing Talents of Discipline to Universities (111 project, B13007).

Supplementary information

Supplementary information available online at <http://dev.biologists.org/lookup/doi/10.1242/dev.165688.supplemental>

References

- Albrecht, C., Boutrot, F., Segonzac, C., Schwessinger, B., Gimenez-Ibanez, S., Chinchilla, D., Rathjen, J. P., de Vries, S. C. and Zipfel, C. (2012). Brassinosteroids inhibit pathogen-associated molecular pattern-triggered immune signaling independent of the receptor kinase BAK1. *Proc. Natl. Acad. Sci. USA* **109**, 303-308.
- Ali, G. S., Prasad, K. V. S. K., Day, I. and Reddy, A. S. N. (2007). Ligand-dependent reduction in the membrane mobility of FLAGELLIN SENSITIVE2, an arabidopsis receptor-like kinase. *Plant Cell Physiol.* **48**, 1601-1611.
- Asai, T., Tena, G., Plotnikova, J., Willmann, M. R., Chiu, W.-L., Gomez-Gomez, L., Boller, T., Ausubel, F. M. and Robatzek, S. (2015). MAP kinase signalling cascade in Arabidopsis innate immunity. *Nature* **415**, 977-983.
- Barbieri, E., Di Fiore, P. P. and Sigismund, S. (2016). Endocytic control of signaling at the plasma membrane. *Curr. Opin. Cell Biol.* **39**, 21.
- Belkhadir, Y., Jaillais, Y., Eppe, P., Balsemão-Pires, E., Dangl, J. L. and Chory, J. (2012). Brassinosteroids modulate the efficiency of plant immune responses to microbe-associated molecular patterns. *Proc. Natl. Acad. Sci. USA* **109**, 297.
- Ben Khaled, S., Postma, J. and Robatzek, S. (2015). A moving view: subcellular trafficking processes in pattern recognition receptor-triggered plant immunity. *Annu. Rev. Phytopathol.* **53**, 379-402.
- Boudsocq, M., Willmann, M. R., McCormack, M., Lee, H., Shan, L., He, P., Bush, J., Cheng, S. and Sheen, J. (2010). Differential innate immune signalling via Ca^{2+} sensor protein kinases. *Nature* **464**, 418-422.
- Bücherl, C. A., Jarsch, I. K., Schudoma, C., Segonzac, C., Mbengue, M., Robatzek, S., MacLean, D., Ott, T. and Zipfel, C. (2017). Plant immune and growth receptors share common signalling components but localise to distinct plasma membrane nanodomains. *eLife* **6**, 1-28.
- Cacas, J.-L., Furt, F., Le Guédard, M., Schmitte, J.-M., Buré, C., Gerbeau-Pissot, P., Moreau, P., Bessoule, J.-J., Simon-Plas, F. and Mongrand, S. (2012). Lipids of plant membrane rafts. *Prog. Lipid Res.* **51**, 272-299.
- Cao, Y., Aceti, D. J., Sabat, G., Song, J., Makino, S., Fox, B. G. and Bent, A. F. (2013). Mutations in FLS2 Ser-938 dissect signaling activation in FLS2-mediated Arabidopsis immunity. *PLoS Pathog.* **9**, e1003313.
- Carland, F., Fujioka, S. and Nelson, T. (2010). The sterol methyltransferases SMT1, SMT2, and SMT3 influence arabidopsis development through nonbrassinosteroid products. *Plant Physiol.* **153**, 741.
- Chadda, R., Howes, M. T., Plowman, S. J., Hancock, J. F., Parton, R. G. and Mayor, S. (2007). Cholesterol-sensitive Cdc42 activation regulates actin polymerization for endocytosis via the GEEC pathway. *Traffic* **8**, 702-717.
- Clayton, A. H. A., Walker, F., Orchard, S. G., Henderson, C., Fuchs, D., Rothacker, J., Nice, E. C. and Burgess, A. W. (2005). Ligand-induced dimer-tetramer transition during the activation of the cell surface epidermal growth factor

- receptor-A multidimensional microscopy analysis. *J. Biol. Chem.* **280**, 30392-30399.
- Clouse, S. D.** (2002). *Arabidopsis* mutants reveal multiple roles for sterols in plant development. *Plant Cell* **14**, 1995.
- Corriden, R., Kilpatrick, L. E., Kellam, B., Briddon, S. J. and Hill, S. J.** (2014). Kinetic analysis of antagonist-occupied adenosine-A3 receptors within membrane microdomains of individual cells provides evidence of receptor dimerization and allosterism. *FASEB J.* **28**, 4211-4222.
- Danna, C. H., Millet, Y. A., Koller, T., Han, S.-W., Bent, A. F., Ronald, P. C. and Ausubel, F. M.** (2011). The *Arabidopsis* flagellin receptor FLS2 mediates the perception of *Xanthomonas* Ax21 secreted peptides. *Proc. Natl. Acad. Sci. USA* **108**, 9286-9291.
- Das, S. K., Darshi, M., Cheley, S., Wallace, M. I. and Bayley, H.** (2007). Membrane protein stoichiometry determined from the step-wise photobleaching of dye-labelled subunits. *ChemBiochem* **8**, 994-999.
- de Heus, C., Kagie, N., Heukers, R., van Bergen en Henegouwen, P. M. P. and Gerritsen, H. C.** (2013). Analysis of EGF receptor oligomerization by homo-FRET. *Method Cell Biol.* **117**, 305-321.
- Diener, A. C., Li, H., Zhou, W., Whoriskey, W. J., Nes, W. D. and Fink, G. R.** (2000). Sterol methyltransferase 1 controls the level of cholesterol in plants. *Plant Cell* **12**, 853-870.
- Dodds, P. N. and Rathjen, J. P.** (2010). Plant immunity: towards an integrated view of plant-pathogen interactions. *Nat. Rev. Genet.* **11**, 539-548.
- Doherty, G. J. and McMahon, H. T.** (2009). Mechanisms of endocytosis. *Annu. Rev. Biochem.* **78**, 857-902.
- Du, Y., Tejos, R., Beck, M., Himschoot, E., Lia, H., Robatzek, S., Vanneste, S. and Friml, J.** (2013). Salicylic acid interferes with clathrin-mediated endocytic protein trafficking. *Proc. Natl. Acad. Sci. USA* **110**, 7946-7951.
- Fan, L., Li, R., Pan, J., Ding, Z. and Lin, J.** (2015). Endocytosis and its regulation in plants. *Trends Plant Sci.* **20**, 388-397.
- Felix, G., Duran, J. D., Volk, S. and Boller, T.** (1999). Plants have a sensitive perception system for the most conserved domain of bacterial flagellin. *Plant J.* **18**, 265-276.
- Ferrer, A., Altabella, T., Arró, M. and Boronat, A.** (2017). Emerging roles for conjugated sterols in plants. *Prog. Lipid Res.* **67**, 27-37.
- Flores-Otero, J., Ahn, K. H., Delgado-Peraza, F., Mackie, K., Kendall, D. A. and Yudowski, G. A.** (2014). Ligand-specific endocytic dwell times control functional selectivity of the cannabinoid receptor 1. *Nat. Commun.* **5**, 4589.
- Gao, J., Wang, Y., Cai, M., Pan, Y., Xu, H., Jiang, J., Ji, H. and Wang, H.** (2015). Mechanistic insights into EGFR membrane clustering revealed by super-resolution imaging. *Nanoscale* **7**, 2511-2519.
- Gómez-Gómez, L. and Boller, T.** (2000). FLS2: an LRR receptor-like kinase involved in the perception of the bacterial elicitor flagellin in *Arabidopsis*. *Mol. Cell* **5**, 1003-1011.
- Grebe, M., Xu, J., Möbius, W., Ueda, T., Nakano, A., Geuze, H. J., Rook, M. B. and Scheres, B.** (2003). *Arabidopsis* sterol endocytosis involves actin-mediated trafficking via ARA6-positive early endosomes. *Curr. Biol.* **13**, 1378-1387.
- Grossie, D. A., Turnbull, K., Felix-Balderrama, S. and Raghavapuram, S.** (2009). 3-(2-Acetamido-phen-yl)sydnone. *Acta Crystallogr. C* **65**, 554-555.
- Hao, H., Fan, L., Chen, T., Li, R., Li, X., He, Q., Botella, M. A. and Lin, J.** (2014). Clathrin and membrane microdomains cooperatively regulate RbohD dynamics and activity in *Arabidopsis*. *Plant Cell* **26**, 1729-1745.
- Heese, A., Hann, D. R., Gimenez-Ibanez, S., Jones, A. M. E., He, K., Li, J., Schroeder, J. I., Peck, S. C., John, P. and Rathjen, J. P.** (2007). The receptor-like kinase SERK3/BAK1 is a central regulator of innate immunity in plants. *Proc. Natl. Acad. Sci. USA* **104**, 12217-12222.
- Henry, E., Yadeta, K. A. and Coaker, G.** (2013). Recognition of bacterial plant pathogens: local, systemic and transgenerational immunity. *New Phytol.* **199**, 908-915.
- Hofman, E. G., Bader, A. N., Voortman, J., van den Heuvel, D. J., Sigismund, S., Verkley, A. J., Gerritsen, H. C. and van Bergen en Henegouwen, P. M. P.** (2010). Ligand-induced EGF receptor oligomerization is kinase-dependent and enhances internalization. *J. Biol. Chem.* **285**, 39481-39489.
- Irani, N. G. and Russinova, E.** (2009). Receptor endocytosis and signaling in plants. *Curr. Opin. Plant Biol.* **12**, 653-659.
- Irani, N. G., Rubbo, S. D., Mylle, E., Begin, J. V. D., Schneider-pizoń, J., Hniliková, J., Šiša, M., Buyst, D., Vilarrasa-Blasi, J., Szatmári, A. et al.** (2012). Fluorescent castasterone reveals BRI1 signaling from the plasma membrane. *Nat. Chem. Biol.* **8**, 583-589.
- Keinath, N. F., Kierszniowska, S., Lorek, J., Bourdais, G., Kessler, S. A., Shimosato-Asano, H., Grossniklaus, U., Schulze, W. X., Robatzek, S. and Panstruga, R.** (2010). PAMP (pathogen-associated molecular pattern)-induced changes in plasma membrane compartmentalization reveal novel components of plant immunity. *J. Biol. Chem.* **285**, 39140-39149.
- Kopischke, M., Westphal, L., Schneeberger, K., Clark, R., Ossowski, S., Wewer, V., Fuchs, R., Landtag, J., Hause, G., Dörmann, P. et al.** (2013). Impaired sterol ester synthesis alters the response of *Arabidopsis thaliana* to *Phytophthora infestans*. *Plant J.* **73**, 456-468.
- Kunze, G., Zipfel, C., Robatzek, S., Niehaus, K., Boller, T. and Felix, G.** (2004). The N terminus of bacterial elongation factor Tu elicits innate immunity in *Arabidopsis* plants. *Plant Cell* **16**, 3496-3507.
- Li, X., Wang, X., Yang, Y., Li, R., He, Q., Fang, X., Luu, D.-T., Maurel, C. and Lin, J.** (2011). Single-molecule analysis of PIP2₁ dynamics and partitioning reveals multiple modes of *Arabidopsis* plasma membrane aquaporin regulation. *Plant Cell* **23**, 3780-3797.
- Li, R., Liu, P., Wan, Y., Chen, T., Wang, Q., Mettbaach, U., Baluška, F., Samaj, J., Fang, X., Lucas, W. J. et al.** (2012). A membrane microdomain-associated protein, *Arabidopsis* Flot1, is involved in a clathrin-independent endocytic pathway and is required for seedling development. *Plant Cell* **24**, 2105-2122.
- Li, X., Luu, D. T., Maurel, C. and Lin, J.** (2013). Probing plasma membrane dynamics at the single-molecule level. *Trends Plant Sci.* **18**, 617-624.
- Li, L., Li, M., Yu, L., Yu, L. Y., Zhou, Z. Y., Liang, X. X., Liu, Z. X., Cai, G. H., Gao, L. Y., Zhang, X. J., et al.** (2014). The FLS2-associated kinase BIK1 directly phosphorylates the NADPH oxidase RbohD to control plant immunity. *Cell Host Microbe* **15**, 329-338.
- Low-Nam, S. T., Lidke, K. A., Cutler, P. J., Roovers, R. C., van Bergen en Henegouwen, P. M. P., Wilson, B. S. and Lidke, D. S.** (2011). ErbB1 dimerization is promoted by domain co-confinement and stabilized by ligand binding. *Nat. Struct. Mol. Biol.* **18**, 1244-1249.
- Malinsky, J., Opekárova, M., Grossmann, G. and Tanner, W.** (2013). Membrane microdomains, rafts, and detergent-resistant membranes in plants and fungi. *Annu. Rev. Plant Biol.* **64**, 501-529.
- Mao, G., Meng, X., Liu, Y., Zheng, Z., Chen, Z. and Zhang, S.** (2011). Phosphorylation of a WRKY transcription factor by two pathogen-responsive MAPKs drives phytoalexin biosynthesis in *Arabidopsis*. *Plant Cell* **23**, 1639-1653.
- Mbengue, M., Bourdais, G., Gervasi, F., Beck, M., Zhou, J., Spallek, T., Bartels, S., Boller, T., Ueda, T., Kuhn, H. et al.** (2016). Clathrin-dependent endocytosis is required for immunity mediated by pattern recognition receptor kinases. *Proc. Natl. Acad. Sci. USA* **113**, 11034-11039.
- McGuire, H., Arousseau, M. R., Bowie, D., and Blunck, R.** (2012). Automating single subunit counting of membrane proteins in mammalian cells. *J. Biol. Chem.* **287**, 35912-35921.
- Men, S., Boutté, Y., Ikeda, Y., Li, X., Palme, K., Stierhof, Y.-D., Hartmann, M.-A., Moritz, T. and Grebe, M.** (2008). Sterol-dependent endocytosis mediates post-cytokinetic acquisition of PIN2 auxin efflux carrier polarity. *Nat. Cell Biol.* **10**, 237-244.
- Monaghan, J. and Zipfel, C.** (2012). Plant pattern recognition receptor complexes at the plasma membrane. *Curr. Opin. Plant Biol.* **15**, 349-357.
- Mulder, L., Lefebvre, B., Cullimore, J. and Imbert, A.** (2006). LysM domains of *Medicago truncatula* NFP protein involved in Nod factor perception. Glycosylation state, molecular modeling and docking of chitooligosaccharides and Nod factors. *Glycobiology* **16**, 801-809.
- Naramoto, S., Kleine-Vehn, J., Robert, S., Fujimoto, M., Dainobu, T., Pacionek, T., Ueda, T., Nakano, A., Van Montagu, M. C. E., Fukuda, H. et al.** (2010). ADP-ribosylation factor machinery mediates endocytosis in plant cells. *Proc. Natl. Acad. Sci. USA* **107**, 21890-21895.
- Niu, Y. and Sheen, J.** (2012). Transient expression assays for quantifying signaling output. *Methods Mol. Biol.* **876**, 195-206.
- Ortiz-Morea, F. A., Savatin, D. V., Dejonghe, W., Kumar, R., Luo, Y., Adamowski, M., Van den Begin, J., Dressano, K., Pereira de Oliveira, G., Zhao, X. et al.** (2016). Danger-associated peptide signaling in *Arabidopsis* requires clathrin. *Proc. Natl. Acad. Sci. USA* **113**, 11028-11033.
- Radutoiu, S., Madsen, L. H., Madsen, E. B., Jurkiewicz, A., Fukai, E., Quistgaard, E. M. H., Albrektsen, A. S., James, E. K., Thirup, S. and Stougaard, J.** (2007). LysM domains mediate lipochitin-oligosaccharide recognition and Nfr genes extend the symbiotic host range. *EMBO J.* **26**, 3923-3935.
- Robatzek, S., Chinchilla, D. and Boller, T.** (2006). Ligand-induced endocytosis of the pattern recognition receptor FLS2 in *Arabidopsis*. *Gene Dev.* **20**, 537-542.
- Roux, M., Schwessinger, B., Albrecht, C., Chinchilla, D., Jones, A., Holton, N., Malinovsky, F. G., Tör, M., de Vries, S. and Zipfel, C.** (2011). The *Arabidopsis* leucine-rich repeat receptor-like kinases BAK1/SERK3 and BKK1/SERK4 are required for innate immunity to hemibiotrophic and biotrophic pathogens. *Plant Cell* **23**, 2440-2455.
- Saka, S. K., Honigsmann, A., Eggeling, C., Hell, S. W., Lang, T. and Rizzoli, S. O.** (2014). Multi-protein assemblies underlie the mesoscale organization of the plasma membrane. *Nat. Commun.* **5**, 4509.
- Schlessinger, J.** (2002). Ligand-induced, receptor-mediated dimerization and activation of EGF receptor. *Cell* **110**, 669-672.
- Segonzac, C. and Zipfel, C.** (2011). Activation of plant pattern-recognition receptors by bacteria. *Curr. Opin. Microbiol.* **14**, 54-61.
- Sigismund, S., Argenzio, E., Tosoni, D., Cavallaro, E., Polo, S. and Di Fiore, P. P.** (2008). Clathrin-mediated internalization is essential for sustained EGFR signaling but dispensable for degradation. *Dev. Cell* **15**, 209-219.
- Simons, K. and Toomre, D.** (2000). Lipid rafts and signal transduction. *Nat. Rev. Mol. Cell Biol.* **1**, 31-39.
- Stanislas, T., Bouyssie, D., Rossignol, M., Vesa, S., Fromentin, J., Morel, J., Pichereaux, C., Monsarrat, B. and Simon-Plas, F.** (2009). Quantitative proteomics

- reveals a dynamic association of proteins to detergent-resistant membranes upon elicitor signaling in Tobacco. *Mol. Cell. Proteomics* **8**, 2186.
- Stanislas, T., Grebe, M. and Boutté, Y.** (2014). Sterol dynamics during endocytic trafficking in Arabidopsis. *Methods Mol. Biol.* **1209**, 13-29.
- Sun, Y., Li, L., Macho, A. P., Han, Z., Hu, Z., Zipfel, C., Zhou, J.-M. and Chai, J.** (2013). Structural basis for flg22-induced activation of the Arabidopsis FLS2-BAK1 immune complex. *Science* **342**, 624-628.
- Ulbrich, M. H. and Isacoff, E. Y.** (2007). Subunit counting in membrane-bound proteins. *Nat. Methods* **4**, 319-321.
- Wang, C., Yan, X., Chen, Q., Jiang, N., Fu, W., Ma, B., Liu, J., Li, C., Bednarek, S. Y. and Pan, J.** (2013). Clathrin light chains regulate clathrin-mediated trafficking, auxin signaling, and development in Arabidopsis. *Plant Cell* **25**, 499-516.
- Wang, L., Li, H., Lv, X., Chen, T., Li, R., Xue, Y., Jiang, J., Jin, B., Baluška, F., Šamaj, J. et al.** (2015). Spatiotemporal dynamics of the BRI1 receptor and its regulation by membrane microdomains in living Arabidopsis cells. *Mol. Plant* **8**, 1334-1349.
- Wang, L., Xue, Y., Xing, J., Song, K. and Lin, J.** (2018). Exploring the spatiotemporal organization of membrane proteins in living plant cells. *Annu. Rev. Plant Biol.* **69**, 525-551.
- Willemsen, V., Friml, J., Grebe, M., Toorn, A., Palme, K. and Scheres, B.** (2003). Cell polarity and PIN protein positioning in Arabidopsis require STEROL METHYLTRANSFERASE1 function. *Plant Cell* **15**, 612-625.
- Xue, Y., Xing, J., Wan, Y., Lv, X., Fan, L., Zhang, Y., Song, K., Wang, L., Wang, X., Deng, X. et al.** (2018). Arabidopsis blue light receptor phototropin 1 undergoes blue light-induced activation in membrane microdomains. *Mol. Plant* **11**, 846-859.
- Yadeta, K. A., Elmore, J. M. and Coaker, G.** (2013). Advancements in the analysis of the Arabidopsis plasma membrane proteome. *Front. Plant Sci.* **4**, 86.
- Yan, S., Mclamore, E. S., Dong, S., Gao, H., Taguchi, M., Wang, N., Zhang, T., Su, X. and Shen, Y.** (2015). The role of plasma membrane H⁽⁺⁾-ATPase in jasmonate-induced ion fluxes and stomatal closure in Arabidopsis thaliana. *Plant J.* **83**, 638-649.
- Yeh, Y. H., Chang, Y. H., Huang, P. Y., Huang, J. B. and Zimmerli, L.** (2015). Enhanced Arabidopsis pattern-triggered immunity by overexpression of cysteine-rich receptor-like kinases. *Front. Plant Sci.* **6**, 322.
- Yu, M., Liu, H., Dong, Z., Xiao, J., Su, B., Fan, L., Komis, G., Šamaj, J., Lin, J. and Li, R.** (2017). The dynamics and endocytosis of Flot1 protein in response to flg22 in Arabidopsis. *J. Plant Physiol.* **215**, 73.
- Zinchuk, V., Wu, Y., Grossenbacher-Zinchuk, O. and Stefani, E.** (2011). Quantifying spatial correlations of fluorescent markers using enhanced background reduction with protein proximity index and correlation coefficient estimations. *Nat. Protoc.* **6**, 1554-1567.