Chitotetraose activates the fungal-dependent endosymbiotic signaling pathway in actinorhizal plant species

Mireille Chabaud, Joëlle Fournier, Lukas Brichet, Iltaf Abdou-Pavy, Leandro Imanishi, Laurent Brottier, Elodie Pirolles, Valérie Hocher, Claudine Franche, Didier Bogusz, et al.

To cite this version:

Mireille Chabaud, Joëlle Fournier, Lukas Brichet, Iltaf Abdou-Pavy, Leandro Imanishi, et al.. Chitotetraose activates the fungal-dependent endosymbiotic signaling pathway in actinorhizal plant species. PLoS ONE, Public Library of Science, 2019, 14 (10), pp.e0223149. 10.1371/journal.pone.0223149. hal-02961598

HAL Id: hal-02961598
https://hal.inrae.fr/hal-02961598
Submitted on 8 Oct 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Distributed under a Creative Commons Attribution 4.0 International License
Chitotetraose activates the fungal-dependent endosymbiotic signaling pathway in actinorhizal plant species

Mireille Chabaud, Joëlle Fournier, Lukas Brichet, Iltaf Abdou-Pavy, Leandro Imanishi, Laurent Brottier, Elodie Pirolles, Valérie Hocher, Claudine Franche, Didier Bogusz, Luis G. Wall, Sergio Svistoonoff, Hassen Gherbi, David G. Barker

1 Laboratory of Plant-Microbe Interactions (INRA/CNRS/University of Toulouse), Castanet-Tolosan, France, 2 Laboratory of Biochemistry, Microbiology and Soil Biological Interactions, Department of Science and Technology, National University of Quilmes, CONICET, Bernal, Argentina, 3 Laboratory of Tropical and Mediterranean Symbioses (IRD/INRA/CIRAD/University of Montpellier/Supagro), Montpellier, France, 4 Plant Diversity, Adaptation and Development (IRD/University of Montpellier), Montpellier, France

a Current address: Laboratory of Biochemistry & Plant Molecular Physiology (INRA/SupAgro/CNRS/University of Montpellier), Montpellier, France.
b Current address: Laboratory of Biology and Genetics of Plant-Pathogen Interactions (INRA/CIRAD/SupAgro), Montpellier, France.
* David.Barker@inra.fr

Abstract

Mutualistic plant-microbe associations are widespread in natural ecosystems and have made major contributions throughout the evolutionary history of terrestrial plants. Amongst the most remarkable of these are the so-called root endosymbioses, resulting from the intracellular colonization of host tissues by either arbuscular mycorrhizal (AM) fungi or nitrogen-fixing bacteria that both provide key nutrients to the host in exchange for energy-rich photosynthates. Actinorhizal host plants, members of the Eurosid 1 clade, are able to associate with both AM fungi and nitrogen-fixing actinomycetes known as Frankia. Currently, little is known about the molecular signaling that allows these plants to recognize their fungal and bacterial partners. In this article, we describe the use of an in vivo Ca^{2+} reporter to identify symbiotic signaling responses to AM fungi in roots of both Casuarina glauca and Discaria tri-nervis, actinorhizal species with contrasting modes of Frankia colonization. This approach has revealed that, for both actinorhizal hosts, the short-chain chitin oligomer chitotetraose is able to mimic AM fungal exudates in activating the conserved symbiosis signaling pathway (CSSP) in epidermal root cells targeted by AM fungi. These results mirror findings in other AM host plants including legumes and the monocot rice. In addition, we show that chitotetraose is a more efficient elicitor of CSSP activation compared to AM fungal lipo-chitooligosaccharides. These findings reinforce the likely role of short-chain chitin oligomers during the initial stages of the AM association, and are discussed in relation to both our current knowledge about molecular signaling during Frankia recognition as well as the different microsymbiont root colonization mechanisms employed by actinorhizal hosts.
Introduction

A limited number of soil microorganisms have acquired the remarkable capacity to colonize plant roots and form mutually beneficial endosymbiotic associations. The most widespread of these are the obligate biotrophic fungi belonging to the Glomeromycota phylum, able to associate with the majority of terrestrial plants resulting in the formation of highly ramified intracellular root cortical structures known as arbuscules [1,2]. Arbuscular mycorrhizal (AM) fungi scavenge vital soil nutrients such as phosphorus, which are then delivered to the host plant via the elaborate symbiotic interface created within arbuscule-containing cortical cells, in exchange for energy-rich metabolites. The AM association is thought to have contributed to the successful establishment of the earliest terrestrial plant species over 400 million years ago [3].

In addition to this ubiquitous fungal symbiosis, certain dicot species belonging to the Eurosid 1 clade subsequently evolved additional beneficial associations with nitrogen-fixing soil bacteria. Gram-negative rhizobia primarily associate with legume Fabales hosts, whilst gram-positive filamentous actinobacteria known as Frankia are able to colonize actinorhizal host species belonging to the Fagales, Cucurbitales and Rosales orders. In the majority of cases the nitrogen-fixing bacteria multiply and differentiate intracellularly within de novo specialized plant organs known as root nodules, thereby providing a valuable source of nitrogen to the host in return for photosynthate-derived resources. Interestingly, initial root colonization by nitrogen-fixing bacteria can be either intra- or intercellular depending upon the host plant [4]. Whilst intracellular root entry via infection thread compartments constructed within root hairs has been well-documented in model legume hosts such as Medicago truncatula [5,6], intercellular modes of colonization in legumes are only poorly understood at the molecular/cellular levels. Both types of root colonization by Frankia have also been observed for actinorhizal hosts [4,7]. For example, intracellular entry via root hairs appears to be common amongst Fagales species such as Alnus glutinosa or Casuarina glauca, whereas intercellular modes of root colonization appear to be predominant for Rosales species typified by Ceanothus spp, Elaeagnus angustifolia or Discaria trinervis [8–10]. In the case of initial root colonization by AM fungi, experiments performed on both legume and non-legume hosts have demonstrated that AM fungal hyphae traverse atrichoblast (non-root hair) cells of the root epidermis within host-constructed transcellular compartments by a mechanism reminiscent of root hair infection thread-mediated colonization by nitrogen-fixing bacterial symbionts [2,3].

An important parameter for the establishment of both AM and nitrogen-fixing endosymbioses is the capacity for mutual recognition of the respective partners. In particular, it is now well-established that host plant perception of appropriate secreted microbial molecules leads to the activation of a Conserved Symbiotic Signaling Pathway (CSSP) required for subsequent microbe root entry [11,12]. A characteristic feature of the CSSP is the triggering of sustained nuclear-associated calcium oscillations which can be conveniently monitored in vivo using fluorescent Ca$^{2+}$ reporters [13,14]. For the large majority of rhizobial-legume associations, decorated lipo-chitooligosaccharides (LCOs) known as nodulation (Nod) factors play this key signaling function, and these LCOs are specifically recognized by host Lysin Motif (LysM) receptor like kinase (RLK) receptor complexes [15,16]. Based on research on legumes such as M. truncatula, there is evidence that chitin-based molecules are also involved in pre-infection AM fungal–host signaling. These include both AM fungal LCOs known as Myc LCOs [17] and AM fungal short-chain chitin oligomers (referred to collectively as Myc COs) and typified by chitotetraose (CO4) [18]. Although the precise roles of these chitinaceous factors remain to be determined, recent studies focused on the monocot rice have confirmed the importance of.
CO4 in AM fungal-host signaling [19], and identified the LysM RLK OsCERK1 as a putative component of the host perception machinery for these fungal-secreted molecules [20].

In contrast with *Rhizobium*-legume associations, relatively little is known about pre-infection microsymbiont-host signaling during the establishment of actinorhizal symbioses. Although strong evidence suggests that intracellular-colonizing *Frankia* which nodulate *A. glutinosa* and *C. glauca* do secrete symbiotic signaling factors, the precise chemical nature of these molecules has not yet been determined. The use of root hair deformation assays, nuclear-localized Ca$^{2+}$ reporters to monitor CSSP activation and the expression of symbiotic reporter genes have together led to the conclusion that these *Frankia* make use of alternative non-chitinaceous signals [21–23]. On the other hand, it is currently unknown whether chitin-based molecules are involved in AM fungal signaling to actinorhizal hosts. In order to investigate this important question, we have made use of the *in vivo* Ca$^{2+}$ reporter approach to evaluate CSSP activation in epidermal root tissues in response to treatment with crude AM fungal exudates as well as potential Myc CO and Myc LCO signaling molecules. The two evolutionarily distant actinorhizal hosts, *C. glauca* and *D. trinervis*, were selected as typical examples of either intracellular or intercellular modes of *Frankia* root colonization. Finally, it is important to underline that, in the absence of either morphological root responses or available AM-related reporter genes for the two actinorhizal hosts, this assay is the only technique currently available for assaying CSSP activation in response to potential AM fungal signaling.

Results presented in this article show that, for both actinorhizal hosts, AM fungal exudates are efficient activators of sustained nuclear Ca$^{2+}$ spiking in root atrichoblasts, the cellular targets for AM root entry. Furthermore, sub-micromolar concentrations of CO4 were able to mimic CSSP activation for the two host plants and were significantly more efficient elicitors of Ca$^{2+}$ spiking compared to the tested Myc LCOs. Interestingly, in contrast to the observed CSSP activation in AM-targeted atrichoblasts, CO4 treatment did not elicit Ca$^{2+}$ spiking in root hairs, the epidermal cells of *C. glauca* which are not colonized by AM fungi. Finally, although responding robustly to AM fungal signaling with CSSP activation, we show that *D. trinervis* atrichoblasts are unresponsive to crude *Frankia* supernatants. Together, these findings underline the cellular specificity of these responses and indicate that actinorhizal host plants represent excellent models for studying endosymbiont-host signaling mechanisms for both intracellular and intercellular colonization.

Materials and methods

Plant materials and growth conditions

Transgenic *C. glauca* plants expressing the nuclear-localised cameleon reporter gene p35S:NUP-YC2.1 [24] were generated via *Agrobacterium tumefaciens* transformation and propagated by taking cuttings as previously described [22]. Transgenic composite plants of *D. trinervis* (also now known as *Ochetophila trinervis*) expressing the p35S:NUP-YC2.1 reporter in roots were obtained using ARquaI *A. rhizogenes*-mediated transformation according to the protocol described in [25]. Transgenic plants were grown in liquid Broughton and Dillworth (BD) medium [26].

Preparation of germinated spore exudates of *Rhizophagus irregularis* and *Frankia* supernatants

*R. irregularis* (Agronutrition, Labège, France) germinated spore exudates (GSEs) were kindly provided by Soizic Rochange and prepared as described in [18] by incubating 125,000 sterile spores in 40 ml of H$_2$O for 7 d in the dark. These GSEs were then concentrated 40-fold and
applied to freshly excised root segments. Cell-free supernatants were prepared from “induced” cultures of Frankia strains which nodulate either C. glauca (Frankia CcI3, referred to in this article as F. casuarinae [27]) or D. trinervis (Frankia BCU110501, referred to in this article as F. discariae [28]). For both F. casuarinae (Fci) and F. discariae (Fdi) supernatants the post-fix “i” refers to the induction of the Frankia cultures by addition of the respective host plant exudates 5 days before harvesting as described in [22, 29]. These induced Frankia supernatants were applied to root segments at a 100-fold dilution.

Chitin-based elicitors

Chitotetraose (CO4) was purchased from Megazym (LIBIOS, Pontcharra, France). An aqueous stock solution of 10⁻³ M CO4 was diluted to either 10⁻⁶ or 10⁻⁸ M. Sulphated and non-sulphated Myc LCOs were kindly provided by Fabienne Maillet and prepared as described in [18]. Since Myc LCO solutions were prepared in diluted acetonitrile, comparative experiments with chitotetraose were performed using CO4 diluted with identical acetonitrile concentrations (0.5% acetonitrile for 10⁻⁶ M CO4 and 0.005% acetonitrile for 10⁻⁸ M CO4).

Nuclear Ca²⁺ spiking responses in C. glauca and D. trinervis roots expressing the p35S:NUP-YC2.1 reporter

Assays for nuclear Ca²⁺ spiking were performed using young lateral root segments (0.5 to 0.8 cm long) freshly excised from hydroponically-grown transgenic plants expressing the p35S:NUP-YC2.1 cameleon reporter. Root explants were placed in a microchamber and treated with 150 µl of the solution to be tested as described in [18]. Confocal FRET-based ratio imaging for detecting and plotting relative changes of nuclear Ca²⁺ levels corresponding to YFP-to-CFP fluorescence intensity changes over time was performed according to [24] using a Leica TCS SP2 AOBS confocal laser-scanning microscope. Imaging was performed on both atrichoblasts and trichoblasts (root hairs) in the case of C. glauca. In contrast, Ca²⁺ spiking responses were only studied in D. trinervis atrichoblasts since few root hairs developed on D. trinervis roots under our growth conditions. It should be underlined that despite limited root hair formation on hydroponically-grown D. trinervis roots, efficient intercellular Frankia colonization and nodulation can be observed on these roots [e.g. 25]. Experiments were repeated several times for each treatment using independent roots (detailed in S1 Table).

Results

Initial outer root colonization by AM fungi is intracellular for both C. glauca and D. trinervis

Late stages of AM fungal colonization have been described for both C. glauca [29–32] and D. trinervis [33]. In both cases, the presence of intracellular symbiotic arbuscules located within inner root cortical cells, accompanied by axially growing intercellular fungal mycelia is consistent with classical Arum-type root colonization [34]. Since the filamentous nitrogen-fixing Frankia microsymbiont penetrates the root outer tissues of these two actinorhizal hosts via contrasting mechanisms, it was essential to examine the initial stages of AM fungal root entry for both species. The images shown in Fig 1 and the accompanying Gif animations (S1 and S2 Figs) are consistent with AM hyphopodium formation on the root surface, followed by intracellular hyphal root penetration of the outer root tissues for the two host plants. This suggests that the AM fungus crosses the epidermal and outer cortical cell layers via a transcellular apoplastic mechanism analogous to what has already been observed for both legume and non-legume hosts [35–37]. Furthermore, initial AM fungal entry for the two actinorhizal hosts
occurs exclusively via epidermal atrichoblasts, again similar to earlier findings for other AM hosts [38]. Thus, despite striking differences in the modes of Frankia root colonization for C. glauca and D. trinervis, it is likely that comparable cellular mechanisms operate during initial root entry of the AM fungal partner.

AM fungal spore exudates trigger sustained Ca\(^{2+}\) spiking in the root epidermis of actinorhizal host plants

Our next objective was to investigate the capacity of AM fungal signals to activate the CSSP in actinorhizal host epidermal tissues, focusing primarily on AM-targeted atrichoblast cells. For this we exploited transgenic plant tissues expressing the cameleon sensor Nup-YC2.1 in order to detect nuclear-associated Ca\(^{2+}\) oscillations characteristic of CSSP activation [24]. In the case of C. glauca, stable Nup-YC2.1-expressing lines were already available as described in [22]. For D. trinervis, composite plants expressing Nup-YC2.1 in root tissues were obtained via A. rhizogenes-mediated transformation (see Materials & Methods; [25,39]).

Initially, we examined whether crude exudates of germinated AM spores were able to activate the characteristic symbiotic nuclear Ca\(^{2+}\) spiking response in atrichoblasts of both actinorhizal host plants. Young lateral root segments were harvested from plants growing in liquid medium and treated with a 40x concentrated solution of a R. irregularis germinated spore exudate (GSE) as described in [18]. Changes in nuclear Ca\(^{2+}\) levels within root atrichoblasts were recorded over a 20 min period. Compared with H\(_2\)O controls (Fig 2A and 2B), GSE treatment activated sustained nuclear Ca\(^{2+}\) oscillations (spiking) in 80–90% of root atrichoblasts, whether from C. glauca or D. trinervis roots (Fig 2C and 2D). Having established that the CSSP can be activated by AM fungal exudates in the D. trinervis epidermis, we then evaluated responses to a diluted supernatant from the F. discaariae strain that nodulates D. trinervis (supernatants from host root exudate-induced cultures were prepared as described in [22]). Strikingly, the F. discaariae (Fdi) supernatant was unable to elicit Ca\(^{2+}\) spiking in the D. trinervis root (Fig 2F), despite the fact that intercellular Frankia root colonization takes place between atrichoblast
cells [10,25]. This contrasts with the situation for *C. glauca*, where, as previously shown, supernatants from the induced *F. casuarinae* strain (Fci) trigger sustained spiking in *C. glauca* root hairs, the target cells for intracellular colonization [22] (Fig 2E).

**CO4 mimics the activation of symbiotic Ca\(^{2+}\) spiking by fungal GSEs in the two actinorhizal hosts**

The short-chain chitin oligomer chitotetraose (CO4) is able to activate the AM-dependent CSSP of both legume and non-legume hosts at sub-micromolar concentrations [18,19]. We therefore tested the capacity of CO4 to trigger nuclear Ca\(^{2+}\) spiking in root atrichoblasts of *C. glauca* and *D. trinervis* at both \(10^{-6}\) M and \(10^{-8}\) M. Data presented in Fig (3A–3D) show that both concentrations of CO4 elicit pronounced and sustained Ca\(^{2+}\) spiking responses similar to those observed with AM fungal GSEs (Fig 2). Percentages of responding cells ranged from 75–90% and were marginally higher when CO4 was added at \(\mu\)M levels. In contrast to AM fungi, *F. casuarinae* initially colonizes *C. glauca* root hairs, and as shown above, *Frankia* supernatants elicit Ca\(^{2+}\) spiking in these epidermal cells (Fig 2E). For this reason, we also evaluated the reactivity of *C. glauca* root hairs to exogenous \(10^{-8}\) M CO4. Out of the 20 root hairs examined (from three independent root segments), not a single cell responded positively to the Myc CO elicitor (Fig 3E). These findings therefore demonstrate that chitotetraose can mimic the activation of the CSSP by AM fungal GSEs in root atrichoblasts of both actinorhizal host plants, but is not able to trigger nuclear Ca\(^{2+}\) spiking in *C. glauca* root hairs.
Myc LCOs are less efficient elicitors of nuclear Ca\textsuperscript{2+} spiking in actinorhizal hosts as compared to CO4. In addition to Myc COs such as CO4, other chitin-based molecules have been identified as potential AM fungal symbiotic signals. LCOs, which structurally resemble rhizobial Nod factors, are also present in AM fungal exudates, and have been shown to activate the CSSP in legume hosts [17–19]. Myc LCOs are present in both sulphated (S-Myc LCOs) and non-sulphated forms (NS-Myc LCOs) in exudates of \textit{R. irregularis} [17]. For comparative purposes, we therefore evaluated nuclear Ca\textsuperscript{2+} spiking initiation in both \textit{C. glauca} and \textit{D. trinervis} root atrichoblasts in response to either S-Myc LCOs or NS-Myc LCOs. These experiments, summarized in \textbf{S1 Table} and in histogram form in \textbf{Fig 4}, reveal that both sulphated and non-sulphated Myc LCOs are capable of triggering Ca\textsuperscript{2+} oscillations in both \textit{C. glauca} and \textit{D. trinervis} root atrichoblasts in response to either S-Myc LCOs or NS-Myc LCOs. These experiments, summarized in \textbf{S1 Table} and in histogram form in \textbf{Fig 4}, reveal that both sulphated and non-sulphated Myc LCOs are capable of triggering Ca\textsuperscript{2+} oscillations in both \textit{C. glauca} and \textit{D. trinervis} root atrichoblasts (illustrated for NS-Myc LCOs in \textbf{S3 Fig}). However, these data also show that Myc LCOs are significantly less active than CO4 in triggering the CSSP in both actinorhizal hosts, and that S-Myc LCOs are even less active than NS-Myc LCOs. In the case of \textit{C. glauca}, the difference between CO4 and S-Myc LCO activity can be best appreciated at the lower 10\textsuperscript{-8} M concentration. Note also that, since spiking was only observed in 20\% of atrichoblasts at 10\textsuperscript{-8} M S-Myc LCO, experiments were not performed at the lower concentration of 10\textsuperscript{-6} M. Although a similar overall trend was found for both actinorhizal hosts, the ability to discriminate between CO4 and NS-Myc LCOs appears greater for \textit{D. trinervis} by comparison with \textit{C. glauca} (\textbf{Fig 4}). This difference can also be appreciated in the representative Ca\textsuperscript{2+} spiking profiles shown in \textbf{S3 Fig}, where 10\textsuperscript{-6} M NS-Myc LCO elicits a response with lower spiking periodicity in the \textit{D. trinervis} epidermis as compared to \textit{C. glauca}. Taken together, we conclude that
chitotetraose is a more efficient elicitor of CSSP activation in the actinorhizal host root epidermis compared to the two types of Myc LCOs evaluated in this study.

**Discussion**

In this article we have investigated early symbiotic signaling between AM fungi and the two distantly-related actinorhizal host plants, *C. glauca* and *D. trinervis*, examples of either intracellular or intercellular *Frankia* root colonization respectively. Host perception of AM fungal signals was studied for both plants using a nuclear-localized Ca\(^{2+}\) reporter to monitor the activation of the conserved symbiotic signal transduction pathway (CSSP) in epidermal root tissues. This approach has revealed that AM fungal spore exudates (GSEs) elicit sustained nuclear Ca\(^{2+}\) spiking in root atrichoblasts of both *C. glauca* and *D. trinervis* (Fig 2) when applied at doses equivalent to those used previously for the legume *M. truncatula* [18]. This finding is coherent with the observation that, for all three host plants, AM fungal root entry is intracellular, with atrichoblasts as the principal epidermal target (Fig 1).

Earlier studies had shown that short-chain chitin oligomers such as CO4/CO5 are present in AM fungal GSEs and furthermore that 10\(^{-8}\) M CO4 is sufficient to mimic GSE-elicited Ca\(^{2+}\) spiking in *M. truncatula* roots [18]. We show here that the same concentration of CO4 is able to trigger spiking responses in root atrichoblasts of both *C. glauca* and *D. trinervis* (Fig 2) when applied at doses equivalent to those used previously for the legume *M. truncatula* [18]. This finding is coherent with the observation that, for all three host plants, AM fungal root entry is intracellular, with atrichoblasts as the principal epidermal target (Fig 1).

Fig 4. Chitotetraose is a more efficient elicitor of Ca\(^{2+}\) spiking in root atrichoblasts of both *C. glauca* and *D. trinervis* by comparison with Myc LCOs. Root segments of both actinorhizal host plants were treated with either GSEs (40x concentrated), CO4 (10\(^{-8}\) & 10\(^{-6}\) M), non-sulphated (NS)-Myc LCOs (10\(^{-8}\) & 10\(^{-6}\) M), or sulphated (S)-Myc LCOs (10\(^{-6}\) M). For each treatment the dark grey bars indicate the percentage of atrichoblast cells with more than 2 spikes within the 20 min imaging period, the light grey bars 1–2 spikes, and the white bars represent non-spiking cells. See S1 Table for details of the number of cells examined for each condition and note that the data presented in this figure for all the CO4 and Myc-LCO treatments were obtained in the presence of acetonitrile (0.005% for 10\(^{-8}\) M dilutions and 0.5% for 10\(^{-6}\) M dilutions).

https://doi.org/10.1371/journal.pone.0223149.g004

chitotetraose is a more efficient elicitor of CSSP activation in the actinorhizal host root epidermis compared to the two types of Myc LCOs evaluated in this study.
atrichoblasts, the cellular targets for AM colonization. Furthermore, for certain hosts, such as rice [19] and C. glauca (Fig 3) this response is cell-specific by comparison with root hairs (see below). Additional direct evidence favoring the role of Myc COs as signaling molecules in the initial establishment of the AM association has come from the recent finding that AM-defective Oscerk1 rice mutants are also defective in responding to CO4 [20], thus suggesting that Myc COs are perceived by a novel rice receptor complex comprising OsCERK1 associated with a second CO-binding LysM-containing membrane protein. Future research now needs to be directed towards identifying the corresponding actinorhizal receptor components capable of recognizing these AM fungal signals and thereby triggering the downstream CSSP. Finally, since LCOs do not appear to be involved in early Frankia-host signaling in the case of C. glauca (see below), the observed low-level responses to Myc LCOs are unlikely to be due to crosstalk with a Frankia-related pathway. In consequence, we interpret this Myc LCO activity as resulting from less efficient perception by the AM-associated receptor compared to Myc COs such as CO4.

As stated earlier, initial root colonization of C. glauca by F. casuarinae occurs intracellularly via root hairs [7]. A variety of host bio-assays, including the expression of transgenic Ca$^{2+}$ reporters, have together revealed that the symbiotic factors present within the Frankia exudate are unlikely to be either LCOs or COs [22,23], and hence this raises the question of the nature of the receptors for Frankia signals in C. glauca. As expected, C. glauca root hairs are the principal cellular targets for Frankia symbiotic signals [29]. The fact that short-chain COs present in AM fungal exudates can only activate the CSSP in root atrichoblasts (Fig 3) leads us to propose that, in the case of C. glauca, receptors responding to either Frankia or AM fungal signals are distinct and specifically localized to the appropriate epidermal target cell. In contrast, the situation differs for D. trinervis, since initial Frankia root colonization occurs intercellularly between adjacent atrichoblasts [10,25]. We show that, although both AM fungal exudates and CO4 trigger nuclear Ca$^{2+}$ spiking in D. trinervis atrichoblasts, spiking is not observed in these cells in response to F. discariae supernatants (Figs 2 and 3). One possible interpretation of these findings is that pre-infection symbiotic signaling leading to host CSSP activation is absent during the initial stages of Frankia colonization of D. trinervis. This question clearly merits further investigation since there is evidence from legumes that CSSP-related signaling may not be required during rhizobial intercellular “crack entry” invasion of certain host species [40,41]. In conclusion, the results presented in this article indicate that actinorhizal host plants are particularly valuable model systems for comparative studies of endosymbiont-host signaling mechanisms associated with either intracellular or intercellular root colonization.

Supporting information
S1 Fig. Animated Gif of superimposed images from a site of AM fungal colonization of a D. trinervis root corresponding to (Fig 1C and 1D).
(GIF)

S2 Fig. Animated Gif of superimposed images from a second site of AM fungal colonization of a D. trinervis root.
(GIF)

S3 Fig. Nuclear Ca$^{2+}$ spiking profiles in root atrichoblasts of the two actinorhizal host plants in response to $10^{-6}$ M NS-Myc LCOs. These representative profiles reflect the lower reactivity of D. trinervis atrichoblasts to NS-Myc LCOs as illustrated in histogram form in Fig 4.
(PDF)
S1 Table. Summary of the Ca\textsuperscript{2+} spiking responses for each treatment including the number of independent roots and the number of cells observed. For each treatment, cells were assigned to one of the three categories presented in histogram format in Fig 4 (non-responding cells, cells with 1–2 spikes/20 min and cells with more than 2 spikes/20 min). Note that, in the case of CO4 treatment, the numbers in brackets refer to the roots/cells treated with CO4 in the presence of acetonitrile (0.005% for 10\textsuperscript{-8} M CO4 and 0.5% for 10\textsuperscript{-6} M CO4; see Materials & Methods) and correspond to the cells assigned to the three spiking categories.

Atr = atrichoblast; RH = root hair.

Acknowledgments
We would like to thank Soizic Rochange (LRSV, University Paul Sabatier-CNRS, Castanet-Tolosan, France) for kindly providing us with \textit{R. irregularis} GSEs and Fabienne Maillet (LIPM, CNRS-INRA, Castanet Tolosan, France) for providing both sulphated and non-sulphated Myc LCOs. Confocal imaging was performed using the Imagery Platform of the Federated Research Institute (FRAIB) at Castanet-Tolosan.

Author Contributions
Conceptualization: Mireille Chabaud, Joëlle Fournier, Claudine Franche, Didier Bogusz, Sergio Svistoonoff, Hassen Gherbi, David G. Barker.

Funding acquisition: Didier Bogusz, Sergio Svistoonoff, Hassen Gherbi, David G. Barker.

Investigation: Mireille Chabaud, Joëlle Fournier, Lukas Brichet, Iltaf Abdou-Pavy.

Methodology: Lukas Brichet, Iltaf Abdou-Pavy, Leandro Imanishi, Laurent Brottier, Elodie Pirolles, Luis G. Wall, Sergio Svistoonoff.

Project administration: Hassen Gherbi, David G. Barker.

Resources: Leandro Imanishi, Laurent Brottier, Elodie Pirolles, Valérie Hocher, Luis G. Wall, Sergio Svistoonoff, Hassen Gherbi.

Supervision: Mireille Chabaud, Joëlle Fournier, Valérie Hocher, Luis G. Wall, Sergio Svistoonoff, Hassen Gherbi, David G. Barker.

Visualization: Mireille Chabaud, Joëlle Fournier.

Writing – original draft: David G. Barker.

Writing – review & editing: Mireille Chabaud, Joëlle Fournier, Claudine Franche, Luis G. Wall, Sergio Svistoonoff, Hassen Gherbi, David G. Barker.

References
1. Bonfante P, Genre A. Plants and arbuscular mycorrhizal fungi: an evolutionary-developmental perspective. Trends in Plant Science. 2008; 13:492–8. https://doi.org/10.1016/j.tplants.2008.07.001 PMID: 18701339
2. Parniske M. Arbuscular mycorrhiza: the mother of plant root endosymbioses. Nature Reviews Microbiology. 2008; 6:763–75. https://doi.org/10.1038/nrmicro1987 PMID: 18794914
3. Martin FM, Uroz S, Barker DG. Ancestral alliances: Plant mutualistic symbioses with fungi and bacteria. Science. 2017; 356:aad4501.
4. Ibañez F, Wall L, Fabra A. Starting points in plant-bacteria nitrogen-fixing symbioses: intercellular invasion of the roots. Journal of Experimental Botany. 2017; 68:1905–18. https://doi.org/10.1093/jxb/erw367 PMID: 27756807
5. Fournier J, Timmers ACJ, Sieberer BJ, Jauneau A, Chabaud M, Barker DG. Mechanism of infection thread elongation in root hairs of *Medicago truncatula* and dynamic interplay with associated rhizobial colonization. Plant Physiology. 2008; 148:1985–95. https://doi.org/10.1104/pp.108.125674 PMID: 18931145

6. Gage DJ. Infection and invasion of roots by symbiotic, nitrogen-fixing rhizobia during nodulation of temperate legumes. Microbiology and Molecular Biology Reviews. 2004; 68:280–300. https://doi.org/10.1128/MMBR.68.2.280-300.2004 PMID: 15187185

7. Svistoonoff S, Hocher V, Gherbi H. Arbuscular root nodule symbiosis: what is signalling telling about the origins of nodulation? Current Opinion in Plant Biology. 2014; 20:11–18. https://doi.org/10.1016/j. pbi.2014.03.001 PMID: 24691197

8. Liu Q, Berry AM. The infection process and nodule initiation in the *Frankia-Ceanothus* root nodule symbiosis—a structural and histochemical study. Protoplasma. 1991; 163:92–822.

9. Miller IM, Baker DD. The initiation, development and structure of root nodules in *Elaeagnus angustifolia* L. (*Elaeagnaceae*). Protoplasma. 1985; 128:107–119.

10. Valverde C, Wall LG. Time course of nodule development in the *Discaria trinervis* (*Rhamnaceae*) *Frankia* symbiosis. New Phytologist. 1999; 141:345–54.

11. Gutjahr C, Parmiske M. Cell and developmental biology of arbuscular mycorrhiza symbiosis. Annual Review of Cell and Developmental Biology. 2013; 29:593–617. https://doi.org/10.1146/annurev-cellbio-101512-122413 PMID: 24099088

12. Oldroyd GED. Speak, friend, and enter: signalling systems that promote beneficial symbiotic associations in plants. Nature Reviews Microbiology. 2013; 11:252–63. https://doi.org/10.1038/nrmicro2990 PMID: 23493145

13. Barker DG, Chabaud M, Russo G, Genre A. Nuclear Ca\(^{2+}\) signalling in arbuscular mycorrhizal and actinorhizal endosymbioses: on the trail of novel underground signals. New Phytologist. 2017; 214:533–8. https://doi.org/10.1111/nph.11050 PMID: 27918078

14. Miwa H, Sun J, Oldroyd GED, Downie JA. Analysis of calcium spiking using a cameleon calcium sensor reveals that nodulation gene expression is regulated by calcium spike number and the developmental status of the cell. Plant Journal. 2006; 48:883–94. https://doi.org/10.1111/j.1365-313X.2006.02926.x PMID: 17227545

15. Antolin-Lloreta M, Petutsching EK, Ried MK, Lipka V, Nurnberger T, Robatzek S, et al. Knowing your friends and foes—plant receptor-like kinases as initiators of symbiosis or defence. New Phytologist. 2014; 204:791–802. https://doi.org/10.1111/j.1365-313X.2013.02293.x PMID: 25367611

16. Zipfel C, Oldroyd GED. Plant signalling in symbiosis and immunity. Nature. 2017; 543:328–36. https://doi.org/10.1038/nature2009 PMID: 28300100

17. Maillet F, Poinsoot V, Andre O, Puech-Pages V, Haouy A, Gueunier M, et al. Fungal lipochitoooligosaccharide symbiotic signals in arbuscular mycorrhiza. Nature. 2011; 469:58–63. https://doi.org/10.1038/nature09622 PMID: 21209659

18. Genre A, Chabaud M, Balzergue C, Puech-Pages V, Novero M, Rey T, et al. Short-chain chitin oligomers from arbuscular mycorrhizal fungi trigger nuclear Ca2+ spiking in *Medicago truncatula* roots and their production is enhanced by strigolactone. New Phytologist. 2013; 198:179–89. https://doi.org/10.1111/j.1111/nph.12120

19. Sun J, Miller JB, Granqvist E, Gobbato E, Maillet F, et al. Activation of symbiosis signaling by arbuscular mycorrhizal fungi in legumes and rice. Plant Cell. 2015; 27:823–38. https://doi.org/10.1105/tpc.114.131326 PMID: 25724637

20. Carotenuto G, Chabaud M, Miyata K, Capozzi M, Takeda N, Kaku H, et al. The rice LysM receptor-like kinase OsCERK1 is required for the perception of short-chain chitin oligomers in arbuscular mycorrhizal signaling. New Phytologist. 2017; 214:1440–6. https://doi.org/10.1111/nph.14539 PMID: 28369864

21. Céron-Hone P, Debelle F, Fernandez MP. Structural and functional comparison of *Frankia* root hair deforming factor and rhizobia Nod factor. Canadian Journal of Botany. 1999; 77:1293–301.

22. Chabaud M, Gherbi H, Pirolles E, Vaissayre V, Fournier J, Moukouanga D, et al. Chitinase-resistant hydrophilic symbiotic factors secreted by *Frankia* activate both Ca2+ spiking and NIN gene expression in the actinorhizal plant *Casuarina glauca*. New Phytologist. 2016; 209:86–93. https://doi.org/10.1111/nph.13732 PMID: 26484850

23. Cissoko M, Hocher V, Gherbi H, Gully D, Carre-Mlouka A, Sane S, et al. Actinorhizal signaling molecules: *Frankia* root hair deforming factor shares properties with NIN-inducing factor. Frontiers in Plant Science. 2018; 9:1494. https://doi.org/10.3389/fpls.2018.01494 PMID: 30405656

24. Sieberer BJ, Chabaud M, Timmers AC, Monin A, Fournier J, Barker DG. A nuclear-targeted cameleon demonstrates intranuclear Ca2+ spiking in *Medicago truncatula* root hairs in response to rhizobial...
nodule formation. Plant Physiology. 2009; 151:1197–206. https://doi.org/10.1104/pp.109.142851 PMID: 19705633

25. Fournier J, Imanishi L, Chabaud M, Abdou-Pavy I, Genre A, Brichet L, et al. Cell remodeling and subtilase gene expression in the actinorhizal plant Discaria trinervis highlight high host orchestration of intercellular Frankia colonization. New Phytologist. 2018; 219:1018–30. https://doi.org/10.1111/nph.15216 PMID: 29790172

26. Svistoonoff S, Sy MO, Diagne N, Barker DG, Bogusz D, Franche C. Infection-specific activation of the Medicago truncatula Enod11 early nodulin gene promoter during actinorhizal root nodulation. Molecular Plant-Microbe Interactions. 2010; 23:740–7. https://doi.org/10.1094/MPMI-23-6-0740 PMID: 20459313

27. Nouioui I, Ghodhbane-Gtari F, Montero-Calasanz MD, Goker M, Meier-Kolthoff JP, Schumann P, et al. Proposal of a type strain for Frankia alni (Woronin 1866) Von Tubeuf 1895, emended description of Frankia alni, and recognition of Frankia casuarinae sp nov and Frankia elaeagni sp nov. International Journal of Systematic and Evolutionary Microbiology. 2016; 66:5201–10. https://doi.org/10.1099/ijsem.0.01496 PMID: 27624710

28. Nouioui I, Montero-Calasanz MD, Ghodhbane-Gtari F, Rohde M, Tisa LS, Klenk HP, et al. Frankia discariae sp nov.: an infective and effective microsymbiont isolated from the root nodule of Discaria trinervis. Archives of Microbiology. 2017; 199(5):641–7. https://doi.org/10.1007/s00203-017-1337-6 PMID: 28105605

29. Clavijo F, Diedhiou I, Vaissayre V, Brottier L, Acolatse J, Moukaoua D, et al. The Casuarina NIN gene is transcriptionally activated throughout Frankia root infection as well as in response to bacterial diffusible signals. New Phytologist. 2015; 208:887–903. https://doi.org/10.1111/nph.13906 PMID: 26096779

30. Gherbi H, Markmann K, Svistoonoff S, Estevan J, Autran D, Giczy G, et al. SymRK defines a common genetic basis for plant root endosymbioses with arbuscular mycorrhiza fungi, rhizobia, and Frankia bacteria. Proceedings of the National Academy of Sciences of the United States of America. 2008; 105:4928–32. https://doi.org/10.1073/pnas.0710618105 PMID: 18316735

31. Diagne N, Escoute J, Lartaud M, Verdeil JL, Franche C, Kane A, et al. Uvitex2B: a rapid and efficient stain for detection of arbuscular mycorrhizal fungi within plant roots. Mycorrhiza. 2011; 21:315–21. https://doi.org/10.1007/s00572-010-0357-8 PMID: 21225294

32. Svistoonoff S, Benabdou FM, Nambiar-Veetil M, Imanishi L, Vaissayre V, Cesari S, et al. The independent acquisition of plant root nitrogen-fixing symbiosis in Fabids recruited the same genetic pathway for nodule organogenesis. PloS One. 2013; 8:e64515. https://doi.org/10.1371/journal.pone.0064515 PMID: 23741336

33. Obertello M, Wall LG. Interactions between Frankia BCU110501 (actinorhiza) and Gigaspora rosea (arbuscular mycorrhiza) with Discaria trinervis studied by spot inoculation. Symbiosis. 2015; 66:13–20.

34. Smith SE, Reed DJ. Mycorrhizal Symbiosis. London, UK: Elsevier. 2008.

35. Bonfante P, Genre A, Faccio A, Martini I, Schauser L, Stougaard J, et al. The Lotus japonicus LjSym4 gene is required for the successful symbiotic infection of root epidermal cells. Molecular Plant-Microbe Interactions. 2000; 13:1109–20. https://doi.org/10.1094/MPMI.2000.13.10.1109 PMID: 11043472

36. Genre A, Chabaud M, Timmers T, Bonfante P, Barker DG. Arbuscular mycorrhizal fungi elicit a novel intracellular apparatus in Medicago truncatula root epidermal cells before infection. Plant Cell. 2005; 17:3489–99. https://doi.org/10.1105/tpc.105.035410 PMID: 16284314

37. Genre A, Chabaud M, Faccio A, Barker DG, Bonfante P. Prepenetration apparatus assembly precedes and predicts the colonization patterns of arbuscular mycorrhizal fungi within the root cortex of both Medicago truncatula and Daucus carota. Plant Cell. 2008; 20:1407–20. https://doi.org/10.1105/tpc.108.059014 PMID: 18515499

38. Chabaud M, Genre A, Sieberman BJ, Faccio A, Fournier J, Novero M, et al. Arbuscular mycorrhizal hyphopodia and germinated spore exudates trigger Ca²⁺ spiking in the legume and non-legume root epidermis. New Phytologist. 2011; 189:347–55. https://doi.org/10.1111/j.1469-8137.2010.03464.x PMID: 20880223

39. Imanishi L, Vayssieres A, Franche C, Bogusz D, Wall L, Svistoonoff S. Transformed hairy roots of Discaria trinervis: A valuable tool for studying actinorhizal symbiosis in the context of intercellular infection. Molecular Plant-Microbe Interactions. 2011; 24:1317–24. https://doi.org/10.1094/MPMI-03-11-0078 PMID: 21585269

40. Goormachtig S, Capoen W, James EK, Holsters M. Switch from intracellular to intercellular invasion during water stress-tolerant legume nodulation. Proceedings of the National Academy of Sciences of the United States of America. 2004; 101:6303–8. https://doi.org/10.1073/pnas.0401540101 PMID: 15079070
41. Madsen LH, Tirichine L, Jurkiewicz A, Sullivan JT, Heckmann AB, Bek AS, et al. The molecular network governing nodule organogenesis and infection in the model legume *Lotus japonicus*. Nature Communications. 2010; 1:10. https://doi.org/10.1038/ncomms1009 PMID: 20975672