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Correction

PLANT BIOLOGY

Correction for “A role for the mevalonate pathway in early plant symbiotic signaling,” by Muthusubramanian Venkateshwaran, Dhileepkumar Jayaraman, Mireille Chabaud, Andrea Genre, Allison J. Balloon, Junko Maeda, Kari Forshey, Désirée den Os, Nicholas W. Kwiecien, Joshua J. Coon, David G. Barker, and Jean-Michel Ané, which appeared in issue 31, August 4, 2015, of *Proc Natl Acad Sci USA* (112:9781–9786; first published July 21, 2015; 10.1073/pnas.1413762112).

The authors note that, due to a printer’s error, beginning on page 9784, right column, second paragraph, line 8, “*Arabidopsis* does not respond either to rhizobial or AM signals (2, 14) but does to MVA” should instead appear as “*Arabidopsis* does not respond either to rhizobial or AM signals (2, 14) or to MVA.”

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A role for the mevalonate pathway in early plant symbiotic signaling

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Rhizobia and arbuscular mycorrhizal fungi produce signals that are perceived by host legume receptors at the plasma membrane and trigger sustained oscillations of the nuclear and perinuclear Ca²⁺ concentration (Ca²⁺ spiking), which in turn leads to gene expression and downstream symbiotic responses. The activation of Ca²⁺ spiking requires the plasma membrane-localized receptor-like kinase Does not Make Infections 2 (DMI2) as well as the nuclear cation channel DMI1. A key enzyme regulating the mevalonate (MVA) pathway, 3-Hydroxy-3-Methylglutaryl CoA Reductase 1 (HMGR1), interacts with DMI2 and is required for the legume–rhizobium symbiosis. Here, we show that HMGR1 is required to initiate Ca²⁺ spiking and symbiotic gene expression in *Medicago truncatula* roots in response to rhizobial and arbuscular mycorrhizal fungal signals. Furthermore, MVA, the direct product of HMGR1 activity, is sufficient to induce nuclear-associated Ca²⁺ spiking and symbiotic gene expression in both wild-type plants and *dmi2* mutants, but interestingly not in *dmi1* mutants. Finally, MVA induced Ca²⁺ spiking in Human Embryonic Kidney 293 cells expressing DMI1. This demonstrates that the nuclear cation channel DMI1 is sufficient to support MVA-induced Ca²⁺ spiking in this heterologous system.

HMG-CoA reductase | mevalonate | calcium signaling | legume nodulation | arbuscular mycorrhization

The mevalonate (MVA) pathway controls the biosynthesis of hundreds of isoprenoids (sterols, carotenoids, prenyl side chains, etc.) in eukaryotes. These isoprenoids contribute to membrane integrity and development, among many other functions (1). Here, we report that the MVA pathway is also necessary for the earliest responses of plants to symbiotic signals produced by nitrogen-fixing rhizobia and arbuscular mycorrhizal (AM) fungi. These two types of endosymbiotic associations require a common set of genes in host plants to allow successful bacterial and fungal colonization. The molecular mechanisms controlling the establishment of the legume–rhizobium symbiosis have been extensively studied in model legumes such as *Medicago truncatula* and *Lotus japonicus* (2, 3). Rhizobia secrete lipochitooligosaccharides (LCOs) known as nodulation (Nod) factors, which are perceived by LysM-type receptor kinases, such as Nod factor perception (NFP) and LYK3 in *M. truncatula* and are required for both rhizobial infection and nodule organogenesis (4, 5). Similarly, AM fungi release signal molecules, so-called Myc factors, which are likely perceived by other LysM-type receptor kinases in both legumes as well as nonleguminous plants (6–8). The perception of Nod and Myc factors initiates early symbiotic responses in host plants through the activation of the receptor-like kinase Does not Make Infections 2 (DMI2), which is believed to act as a coreceptor (9). Although these signaling components reside on the plasma membrane (10, 11), the perception of symbiotic signals triggers sustained oscillations in Ca²⁺ concentration both within the nucleus (nuclear Ca²⁺ spiking) and around the nucleus (perinuclear

Ca²⁺ spiking) (12, 13). As a result, the generation of second messengers transducing the signals from the plasma membrane to the nuclear envelope has long been hypothesized (12–19).

Elegant mathematical models have been developed to explain the mechanism of nuclear Ca²⁺ spiking and the primary role of DMI1 (a nuclear envelope-localized cation channel) in its initiation and maintenance (13, 18, 20–22). Downstream decoding of Ca²⁺ spiking involves the nuclear Ca²⁺/calmodulin-dependent protein kinase DMI3 (23). In *M. truncatula*, DMI1, DMI2, and DMI3 are essential components of the common symbiosis pathway that is required for establishing both root nodulation and the AM symbiosis, as the respective mutants are defective for both symbioses (2). DMI1 is thus viewed as the first known target of the unidentified second messenger(s) transducing signals from the plasma membrane to the nucleus.

In a previous study, a yeast two-hybrid screen identified a 3-hydroxy 3-methylglutaryl CoA reductase 1 (HMGR1) as strongly interacting with DMI2 (24). HMGRs are well-known regulatory enzymes of the MVA pathway in plants and animals, catalyzing the conversion of HMG-CoA into MVA. Furthermore, the pharmacological inhibition of HMGRs by statin drugs led to decreased nodulation (24). More specifically, silencing *HMGR1* by RNA interference (RNAi) resulted in a drastic reduction in root infection and nodule development (24). However, despite these findings,

Significance

Metabolites of the mevalonate (MVA) pathway play essential roles in the regulation of growth and development in many organisms. In this study, we demonstrate that a key regulatory enzyme of the MVA pathway is directly involved in the signaling pathway that transduces endosymbiotic microbial signals in *Medicago truncatula*. Furthermore, we show that exogenous MVA application is sufficient to activate this transduction pathway. The use of mutants in the signaling pathway and a heterologous expression system provides evidence that the MVA pathway is a missing link between the initial perception of microbial signals at the host plasma membrane and the regulation of symbiotic gene expression in the nucleus.

Author contributions: M.V., D.G.B., and J.-M.A. designed research; M.V., D.J., M.C., A.G., A.J.B., J.M., K.F., and D.d.O. performed research; M.V., A.G., N.W.K., J.J.C., D.G.B., and J.-M.A. contributed new reagents/analytic tools; M.V., D.J., M.C., A.G., A.J.B., J.M., K.F., D.d.O., and J.J.C. analyzed data; and M.V., D.J., A.G., D.G.B., and J.-M.A. wrote the paper.

The authors declare no conflict of interest.

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the precise role of HMGR1 and MVA in symbiosis remained unclear. We now demonstrate that HMGR1 plays a key role during the initial symbiotic signaling between the host plant and both rhizobia and AM fungi. Using pharmacological, biochemical, and genetic approaches, we show that HMGR1 and the products of the MVA pathway act upstream of DMI1 in the symbiotic signaling cascade, providing the missing link between the perception of symbiotic signals at the plasma membrane and the activation of Ca^{2+} spiking in the nucleus.

Results

***M. truncatula* HMGR1 Possesses HMGR Activity.** Because it was a considerable surprise to discover a metabolic enzyme as an interactor of the symbiotic receptor-like kinase DMI2 (24), we investigated whether MtHMGR1 is indeed a bona fide enzyme with HMG-CoA reductase activity. The catalytic domain of HMGR1 was tagged with a maltose-binding protein (MBP:HMGR1 Δ N), expressed in *Escherichia coli*, and purified using amylose resin. Its kinetic properties were studied using spectrophotometry as described in Dale et al. (25). HMG-CoA was used to start the reaction, and the oxidation rate of NADPH was determined before (5 min) and after the addition of HMG-CoA using the absorbance at 340 nm and the initial rate of the reaction was calculated (Fig. S1 A and B). A Lineweaver–Burk plot was used to calculate the V_{max} and K_m of the reaction (Fig. S1D). The apparent V_{max} and $K_m(\text{HMG-CoA})$ were 3.62 ± 0.37 $\mu\text{mol}/\text{min}/\text{mg}$ of protein and 38.88 ± 4.41 μM , respectively. The $K_m(\text{HMG-CoA})$ of MBP:HMGR1 Δ N was thus within the same range as that of other known plant (e.g., rubber, 13 μM ; maize, 10 μM ; *Arabidopsis*, 8 μM) and animal (e.g., rat, 29–47 μM) HMGRs, indicating a similar affinity for HMG-CoA (25–28). We also evaluated the effect of lovastatin, a well-characterized competitive inhibitor of HMGRs, on the enzymatic activity of MtHMGR1. The addition of 50 μM lovastatin completely abolished MBP:HMGR1 Δ N activity (Fig. S1C), thus confirming that HMGR1 has typical HMG-CoA reductase activity. The production of MVA in the HMGR1 reaction mix was determined to be 5 times greater than the control based on the area under the curve corresponding to the extracted ion chromatogram of the MVA standard base peak (Fig. S1E).

HMGR1 Silencing Affects Nod Factor-Induced *ENOD11* Expression and Ca^{2+} Spiking in *M. truncatula*. *M. truncatula* HMGR1 interacts with DMI2, and RNAi-based silencing of *HMGR1* strongly reduces the ability of transgenic roots to develop nodules when inoculated with *Sinorhizobium meliloti* (24). Because a knockout mutant of *HMGR1* was not available, we used the same RNAi-based silencing strategy to investigate the role of *HMGR1* in early symbiotic signaling. We analyzed the induction of nuclear-associated Ca^{2+} spiking and the expression of the *M. truncatula* early nodulin 11 (*ENOD11*) gene, two early symbiotic responses that have been used extensively to study symbiotic signaling (29–31).

ENOD11 expression was analyzed qualitatively in Jemalong A17 plants expressing *pENOD11*-GUS and also quantitatively using RT-PCR. Control *pENOD11*-GUS-expressing roots transformed with the RNAi vector alone displayed the normal dark blue staining 12 h after 10^{-8} M Nod factor addition, whereas *HMGR1*-RNAi roots were only lightly stained (Fig. S2 A and B), thus indicating a clear reduction in reporter expression. This was confirmed by quantitative RT-PCR, which revealed that *ENOD11* expression was approximately eightfold lower in *HMGR1*-RNAi transgenic roots compared with that of the control (Fig. S2C).

Because actively growing root hairs are used for Ca^{2+} measurements, we tested both the effect of silencing *HMGR1* and the effect of inhibiting the MVA pathway on root hair growth. Silencing *HMGR1* had no significant effect on root hair growth (Fig. S3A). Similarly, the application of lovastatin at 0.5 μM , the concentration that reduced nodulation (24), did not affect root hair growth (Fig. S3B). It should be noted that the negative effect

of lovastatin on root hair growth at the higher 1 μM concentration (Fig. S3B) could be due to nonspecific effects. Taken together, these results indicate that the components of the MVA pathway (including *HMGR1*) are not essential for root hair growth.

Nod factor-induced Ca^{2+} spiking was analyzed in *M. truncatula* seedlings expressing both the *HMGR1*-RNAi construct and the Ca^{2+} sensor Yellow Cameleon 3.6 (YC3.6). Transgenic roots expressing YC3.6 alone were used as controls. The application of Nod factors at 10^{-8} M triggered nucleus-associated Ca^{2+} spiking in wild-type control roots 10–15 min after Nod factor application (Fig. 1A). Nod factor-induced Ca^{2+} spiking was not observed in the *nfp-1* mutant (Fig. 1B), which served as a negative control for this experiment. The application of Nod factors failed to trigger detectable Ca^{2+} spiking in epidermal cells of *HMGR1*-silenced roots (Fig. 1C). Ca^{2+} spiking was not detected either in these *HMGR1*-silenced roots in response to germinated spore exudates (GSEs) from the AM fungus *Rhizophagus irregularis* (Fig. S4 A

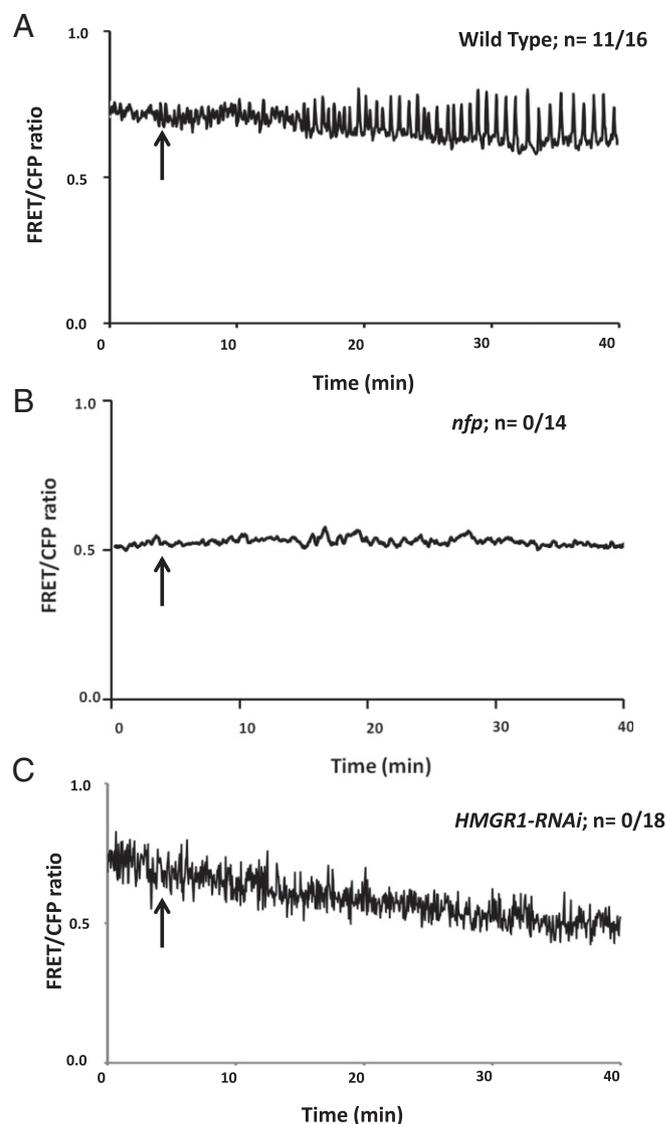


Fig. 1. Effect of silencing *M. truncatula* *HMGR1* on nuclear-associated Ca^{2+} spiking in root epidermal cells. (A) Nod factor-induced Ca^{2+} spiking in *M. truncatula* root hair cells expressing YC3.6. (B) Absence of Nod factor-induced Ca^{2+} spiking in a *nfp* mutant expressing YC3.6. (C) Silencing *HMGR1* abolishes Nod factor-induced Ca^{2+} spiking in *M. truncatula* root hair cells. Arrows indicate the addition of Nod factors.

and *B*). Altogether, these observations indicate that *HMGR1* plays a role in early symbiotic signaling upstream of Ca^{2+} spiking and *ENOD11* expression. We therefore examined whether products of *HMGR1* activity such as MVA are able to elicit Ca^{2+} spiking in root epidermal cells.

MVA Induces *ENOD11* Expression in *M. truncatula* and Ca^{2+} Spiking in Root Epidermal Cells of Legumes and Nonlegumes. To determine whether the product of *HMGR1* activity, MVA, is able to elicit *ENOD11* expression in the absence of Nod factors, *M. truncatula* roots stably transformed with *pENOD11::GUS* were treated with a 100 μM solution of MVA, the lowest concentration required to induce signaling events (*SI Materials and Methods*). Although the responses were weaker compared with Nod factor treatment (Fig. S2D), clear GUS staining was observed in wild-type roots 24 h after MVA treatment (Fig. S2E). However, we were unable to quantify the MVA-induced *ENOD11* expression in *M. truncatula* roots through quantitative RT-PCR, most likely due to the weaker expression of *ENOD11* during MVA treatment compared with Nod factor treatment.

We then investigated whether MVA is also able to activate nuclear-associated Ca^{2+} spiking in the root epidermal cells of *M. truncatula*. The application of the same concentration of MVA triggered sustained Ca^{2+} spiking within 5–10 min in over 50% of cells examined (Fig. 2A). Such MVA-induced Ca^{2+} spiking was also observed in roots of the other model legume, *L. japonicus* (Fig. 2D). Significantly, 100 μM MVA elicited Ca^{2+} spiking (albeit of lower frequency) in epidermal cells of root organ cultures of *M. truncatula* (Fig. 2C). This is particularly interesting, as these root cultures do not respond to rhizobial Nod factors but can be colonized by AM fungi and respond to germinating AM fungal spore exudates (15). Finally, MVA induction of nuclear-associated Ca^{2+} spiking was observed in root organ cultures of carrot, a nonlegume AM host plant (Fig. 2E). In contrast, MVA failed to trigger nuclear-associated Ca^{2+} spiking in trichoblast cells of *Arabidopsis thaliana*, which is unable to develop AM associations or to form root nodules (Fig. 2F).

Taken together, these results suggest that the agonist activity of MVA in relation to Ca^{2+} spiking is comparable for both the rhizobial and AM symbioses, thus potentially placing this metabolite within the common symbiosis pathway. This hypothesis is consistent with the fact that *HMGR1* silencing abolishes Ca^{2+} spiking in root epidermal cells of *M. truncatula* treated with GSE of *R. irregularis* (Fig. S4B). Furthermore, 100 μM MVA restored Ca^{2+} spiking in the same *HMGR1*-silenced roots (Fig. 2B), indicating a direct link between *HMGR1* expression and MVA induced symbiotic signaling.

Because an array of additional metabolites are synthesized from MVA, it is also possible that some of these (isopentenyl pyrophosphate, geranylgeranyl pyrophosphate, etc.) may be responsible for triggering Ca^{2+} spiking in the root epidermis following the exogenous addition of MVA. The application of isopentenyl pyrophosphate (100 μM) did not induce nuclear Ca^{2+} spiking in root epidermal cells (Fig. S5C). Hence, we tested the effect of upstream components of the MVA pathway, such as MVA 5-phosphate and MVA 5-pyrophosphate. Both these phosphorylated versions of MVA triggered nuclear Ca^{2+} spiking in *M. truncatula* root hair cells (Fig. S5A and B). To rule out the possibility that MVA and its phosphorylated versions might induce cytoplasmic acidification, which might account for the generation of nuclear-associated Ca^{2+} spiking, we mimicked such an effect by applying sodium propionate. As shown in Fig. S5D, sodium propionate did not induce Ca^{2+} spiking at concentrations ranging from 100 μM to 1 mM, thus consistent with a specific role for MVA or its immediate downstream products.

MVA-Induced *ENOD11* Expression and Nuclear-Associated Ca^{2+} Spiking Are Dependent on Upstream Components of the Common Symbiosis Pathway. To determine whether MVA-induced *ENOD11* expression

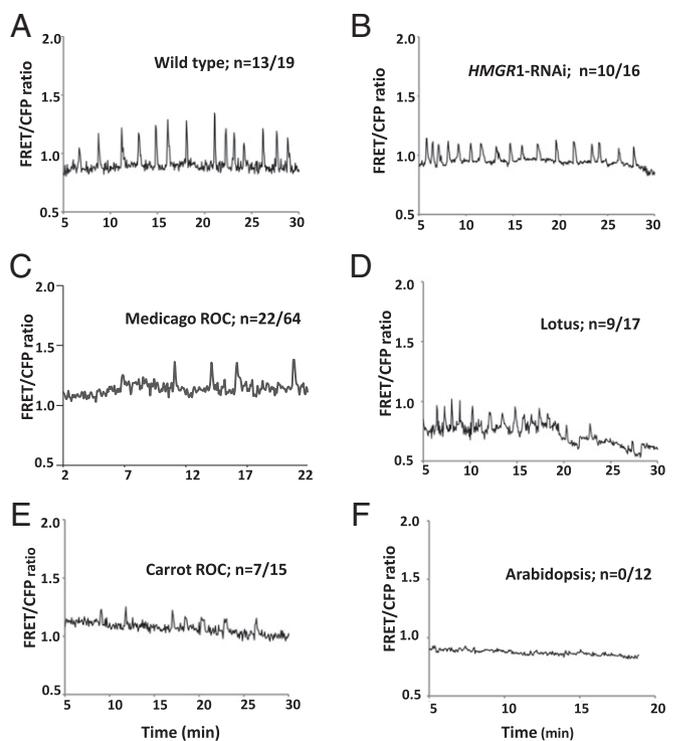


Fig. 2. MVA-induced nuclear-associated Ca^{2+} spiking in legumes and non-legumes. (A) Exogenous application of 100 μM MVA triggers Ca^{2+} spiking in *M. truncatula* root hair cells expressing YC3.6. (B) MVA restores Ca^{2+} spiking in roots silenced for *HMGR1*. (C) MVA induces nuclear Ca^{2+} spiking in atrichoblast cells of a *M. truncatula* root organ culture expressing nuclear-targeted YC2.1. (D) MVA-induced nuclear spiking in root hairs of *L. japonicus* expressing NLS-YC3.6. (E) Atrichoblasts of carrot root organ cultures expressing nuclear-targeted YC2.1 also respond to MVA. (F) In contrast, MVA does not elicit nuclear-associated Ca^{2+} spiking in trichoblast cells of *Arabidopsis* expressing YC3.6, which is unable to form endosymbiotic associations with either rhizobia or AM fungi.

is dependent on the symbiotic signaling pathway, we treated *M. truncatula* *nfp-2*, *dmi1*, *dmi2*, and *dmi3* mutants expressing *pENOD11::GUS* with 100 μM MVA and performed GUS staining 24 h after treatment. MVA induces detectable *ENOD11* expression in *nfp-2* and *dmi2* mutants but not in *dmi1* or *dmi3* mutants, suggesting that *HMGR1*/MVA acts downstream of *DMI2* but upstream of *DMI1* and *DMI3* (Fig. S2 F–I).

Parallel experiments were then performed on MVA-elicited Ca^{2+} spiking using *nfp* and various *dmi* mutants expressing the YC3.6 Ca^{2+} sensor. Consistent with the *ENOD11* expression data, 100 μM MVA triggered nuclear-associated Ca^{2+} spiking in both *dmi2* and *dmi3* mutants but not in *dmi1* mutants (Fig. 3 B–D). Nevertheless, it should be noted that the spiking profile for the *dmi2* mutant had a noisy background as reported previously (32) and that the percentage of responding cells is significantly lower than in wild-type plants (Fig. 2A). On the other hand, MVA-elicited Ca^{2+} spiking was not observed in either trichoblast or atrichoblast cells of two different alleles of *nfp* (*nfp-1* and *nfp-2*; Fig. 3A and Fig. S6). Despite this apparent contradiction with the *ENOD11* expression data for *nfp* (see Discussion), we conclude that MVA itself or the products of the MVA pathway are likely to act downstream of *DMI2* and upstream of *DMI1* in triggering both Ca^{2+} spiking and regulating symbiotic gene expression. This hypothesis is consistent with *HMGR1* acting downstream of its interacting protein partner *DMI2*. To our knowledge, this is the first phenotype that permits the uncoupling of *dmi1* and *dmi2* mutants.

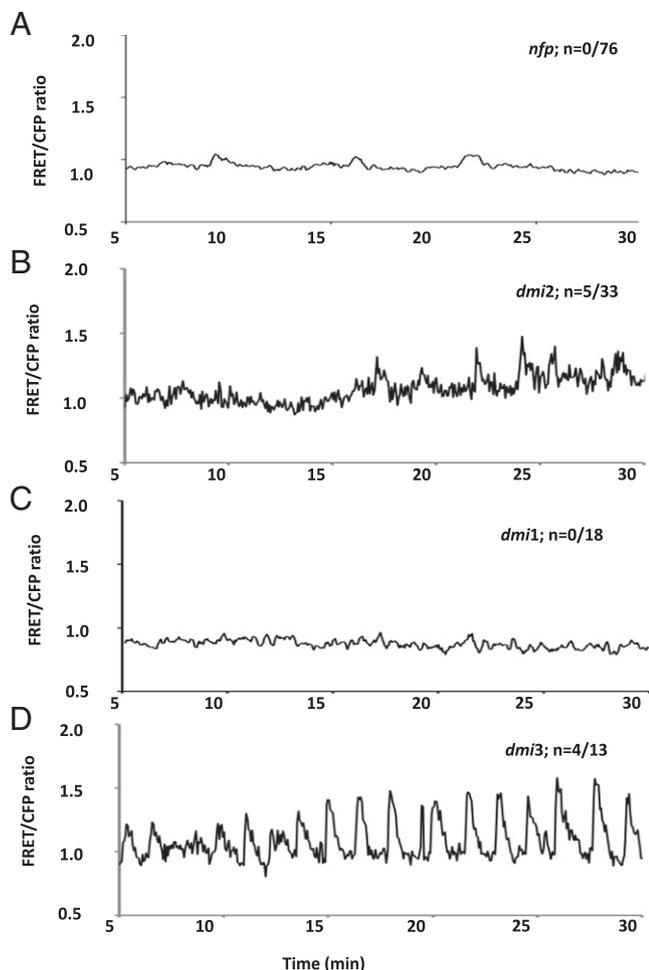


Fig. 3. Analyses of MVA-induced nuclear-associated Ca^{2+} spiking responses in symbiosis-defective mutants of *M. truncatula*. (A) MVA-induced Ca^{2+} spiking was not observed in an *nfp* mutant, which acts upstream of DMI2. (B) MVA activates Ca^{2+} spiking in the *dmi2* mutant expressing YC3.6, (C) but not in the *dmi1* mutant. (D) As expected, MVA-elicited Ca^{2+} spiking is not modified in the *dmi3* mutant, as DMI3 acts downstream of the Ca^{2+} spiking machinery.

MVA Elicits Ca^{2+} Spiking in Human Embryonic Kidney 293 Cells Expressing the *M. truncatula* DMI1 Protein.

To determine whether MVA and DMI1 can be sufficient to trigger Ca^{2+} spiking, we used Human Embryonic Kidney 293 (HEK-293) cells as a heterologous expression system. We have shown in a previous study (18) that DMI1 maintains its nuclear envelope localization in HEK-293 cells when expressed under the control of the cytomegalovirus (CMV) promoter. Furthermore, following exogenous Ca^{2+} treatment, these cells display perinuclear Ca^{2+} oscillations (18). To determine whether MVA can trigger DMI1-mediated Ca^{2+} spiking in HEK-293, this cell line was transfected with either the Ca^{2+} sensor alone (pIRES2-YC3.6) or the Ca^{2+} sensor along with DMI1 (pIRES2-YC3.6::DMI1). For all experiments, the growth medium was replaced by bath solution, either with or without 100 μM MVA. In the absence of MVA, cells expressing pIRES2-YC3.6 or pIRES2-YC3.6::DMI1 did not exhibit de novo Ca^{2+} spiking (Fig. 4A and C). Similarly, the exogenous application of MVA to cells expressing the Ca^{2+} sensor alone did not trigger Ca^{2+} spiking (Fig. 4B). By contrast, MVA application to HEK-293 cells expressing DMI1 triggered an intense Ca^{2+} spiking response (Fig. 4D). These observations, in which DMI1 is expressed as the sole *M. truncatula* protein in a heterologous system, provide further evidence that DMI1 expression is sufficient to support MVA-induced Ca^{2+} spiking.

Discussion

HMGR1 Is Required in the Early Symbiotic Signaling Cascade. Genetic and genomic approaches have advanced our understanding of the molecular mechanisms of signal transduction during the initial stages of legume nodulation and AM symbioses. This research led to the identification of essential components of the common symbiosis pathway (2, 13). However, the secondary messengers that link the perception of microbial signals at the plasma membrane level to the regulation of ion channels and Ca^{2+} pumps on the nuclear envelope remain unknown (17, 33). With the identification of HMGR1 as both an interactor of the DMI2 coreceptor and a requirement for legume nodulation, we hypothesized that this MVA-producing enzyme might function in the common symbiosis signaling pathway. Metabolites from the MVA pathway play a wide variety of roles in many eukaryotes, including growth, development, and responses to environmental stimuli (34–36), by regulating cell-autonomous transcriptional and posttranscriptional processes (36). The observation that silencing *HMGR1* affects Ca^{2+} spiking in response to Nod factors and GSEs of AM fungi supports the hypothesis that HMGR1 is indeed a component of the common symbiosis pathway (Fig. 5). In addition, the study of MVA-induced *ENOD11* expression and Ca^{2+} spiking in various symbiosis-defective mutants indicated that addition of MVA can partly restore *ENOD11* expression and Ca^{2+} spiking in *dmi2* but not in *dmi1* mutants. To our knowledge, this is the first report clearly uncoupling the phenotypes of *dmi1* and *dmi2* mutants. Because DMI1 and DMI2 belong to the common symbiosis pathway, these results place HMGR1 and its MVA-derived products downstream of DMI2 but upstream of DMI1 in the symbiotic cascade (3).

The conversion of HMG-CoA into MVA by HMGR is the first committed and rate-limiting step of the MVA biosynthetic pathway. The ability of MVA to trigger nuclear-associated Ca^{2+} spiking emphasizes the key role of HMGR1 as a link between signaling proteins residing on the plasma membrane and those located on the nuclear envelope. MVA-activated Ca^{2+} spiking is conserved across diverse AM host plants including legumes and nonlegumes. In contrast, the non-AM host *Arabidopsis* does not respond to either rhizobial or AM signals (2, 14), but does to

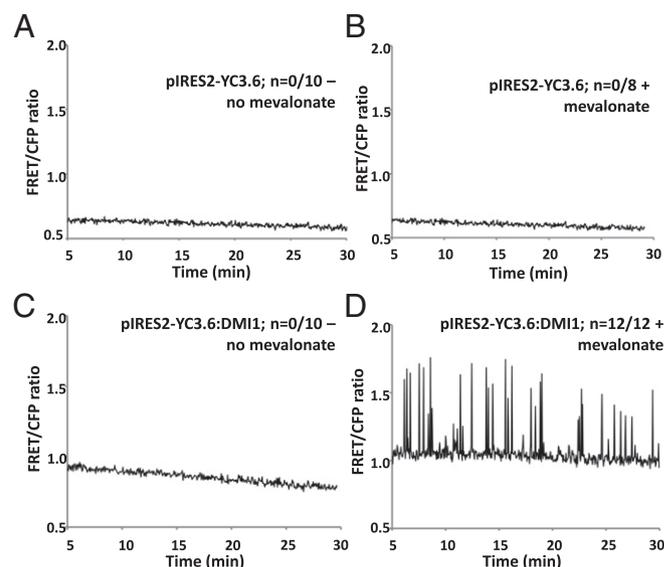


Fig. 4. MVA-induced Ca^{2+} spiking in HEK-293 cells expressing DMI1. (A and B) Absence of Ca^{2+} spiking in HEK-293 cells expressing the vector control pIRES2-YC3.6 in the absence (A) or presence of exogenous MVA (100 μM) (B). (C and D) Ca^{2+} spiking is only observed when MVA is added to HEK-293 cells expressing the pIRES2-YC3.6::DMI1 vector.

Arabidopsis thaliana ecotype Col-0 was transformed with cytosolic YC3.6. GUS assays were performed on Jemalong A17 (*pENOD11::GUS*), *nfp-1* (*pENOD11::GUS*), *nfp-2* (*pENOD11::GUS*), *dmi2-1* (*pENOD11::GUS*), *dmi1-4* (*pENOD11::GUS*), and *dmi3-1* (*pENOD11::GUS*) lines (38, 41). *M. truncatula* and carrot root organ cultures expressing the nuclear NUP-YC2.1 cameleon sensor were obtained via *A. rhizogenes* transformation (15).

For detailed description of methods pertaining to HMGR1 enzymatic assay, RNAi of *MtHMGR1*, *pENOD11::GUS* assays and RT-PCR, root hair growth assays, Ca^{2+} imaging in root epidermal cells, and Ca^{2+} imaging in HEK-293 cells, see *SI Materials and Methods*.

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