Parasitic Worms Stimulate Host NADPH Oxidases to Produce Reactive Oxygen Species That Limit Plant Cell Death and Promote Infection

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Plants and animals produce reactive oxygen species (ROS) in response to infection. In plants, ROS not only activate defense responses and promote cell death to limit the spread of pathogens but also restrict the amount of cell death in response to pathogen recognition. Plants also use hormones, such as salicylic acid, to mediate immune responses to infection. However, there are long-lasting biotrophic plant-pathogen interactions, such as the interaction between parasitic nematodes and plant roots during which defense responses are suppressed and root cells are reorganized to specific nurse cell systems. In plants, ROS are primarily generated by plasma membrane–localized NADPH (reduced form of nicotinamide adenine dinucleotide phosphate) oxidases, and loss of NADPH oxidase activity compromises immune responses and cell death. We found that infection of *Arabidopsis thaliana* by the parasitic nematode *Heterodera schachtii* activated the NADPH oxidases RbohD and RbohF to produce ROS, which was necessary to restrict infected plant cell death and promote nurse cell formation. RbohD- and RbohF-deficient plants exhibited larger regions of cell death in response to nematode infection, and nurse cell formation was greatly reduced. Genetic disruption of *SID2*, which is required for salicylic acid accumulation and immune activation in nematode-infected plants, led to the increased size of nematodes in RbohD- and RbohF-deficient plants, but did not decrease plant cell death. Thus, by stimulating NADPH oxidase–generated ROS, parasitic nematodes fine-tune the pattern of plant cell death during the destructive root invasion and may antagonize salicylic acid–induced defense responses during biotrophic life stages.

INTRODUCTION

NADPH (reduced form of nicotinamide adenine dinucleotide phosphate) oxidase is a heteromultimeric enzyme complex involved in ROS production and immune response in a wide variety of organisms (1). The NADPH oxidase heavy chain subunit gp91phox (also known as CYBB and NOX2) promotes the transfer of electrons to diatomic oxygen to generate superoxide anion (O2−) (2). The generation of superoxide starts a cascade of reactions that result in product of several highly reactive oxygen–derived small molecules collectively called reactive oxygen species (ROS).

Respiratory burst oxidase homologs (Rbohs), the plant homologs of *GP91PHOX*, are encoded by 10 genes in *Arabidopsis thaliana* (*RbohA* to *RbohJ*) (3–5). Rbohs generate ROS in response to bacterial and fungal pathogens (3, 6), and genetic disruption of specific *Rboh* alters plant responses to pathogens (7–9). In *A. thaliana*, loss of *RbohF* enhances cell death and increases resistance to a weakly virulent strain of the oomycete *Hyaloperonospora parasitica* (3). In contrast, in *Nicotiana benthamiana*, silencing of *RbohA* and *RbohB* reduces cell death and impairs plant resistance to infection by the oomycete *Phytophthora infestans* (8). These results point to a pathosystem-specific, sophisticated role of *Rbohs* in plant responses to infection.

Salicylic acid (SA) is a signaling molecule involved in plant defense against infection and interacts with ROS signaling. The concentration of SA increases in cells surrounding the infection site during the hypersensitive resistance response, a mechanism characterized by rapid death of the plant cells surrounding the infection site (10–12). ROS and SA form a feed-forward loop leading to induction of defense gene expression and cell death (13, 14). In *A. thaliana*, loss of the gene encoding the zinc finger protein *LSD1* (lesion stimulating disease 1), which inhibits SA-dependent cell death, results in the increased size of nematodes in RbohD- and RbohF-deficient plants, but does not decrease plant cell death. Thus, by stimulating NADPH oxidase–generated ROS, parasitic nematodes fine-tune the pattern of plant cell death during the destructive root invasion and may antagonize salicylic acid–induced defense responses during biotrophic life stages.

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feeding after J3 (19). Accordingly, syncytia associated with female nematodes are larger than those associated with males (20). Moreover, under adverse conditions, such as nurse cell degeneration in resistant plant genotypes, more male than female nematodes develop. It is unknown whether this phenomenon results from epigenetic influences on sex determination or differences in the mortality of females and males (21, 22). Here, we characterized the role of Rboh-dependent ROS in establishing a biotrophic relationship between A. thaliana and H. schachtii.

RESULTS

RbohD and RbohF promote nematode parasitism

RbohD or RbohF loss of function increases the susceptibility of host plants to infection by fungi or bacteria (3, 6, 8). We asked whether A. thaliana Rboh-family NADPH oxidases were involved in H. schachtii infection. We grew plants in agar medium under sterile conditions, and when the roots had spread through the agar, we inoculated cultures with 60 to 70 nematodes. We found that plants with loss-of-function mutations in rbohD or rbohD and rbohF (rbohD/F), but not rbohA, rbohB, rbohC, rbohE, rbohF, rbohG, or rbohH, showed reduced numbers of female nematodes present within roots 14 days after inoculation (dai) compared to wild-type (Col-0) plants (Fig. 1A and fig. S1A). In addition, the size of female nematodes and syncytia was significantly smaller in the rbohD or rbohD/F plants 14 dai (Fig. 1, B and C, and fig. S1, B and C). We also asked whether overexpression of RbohD in plants could affect nematode infection by assaying 35S::RbohD transgenic plants (16), which expressed four times more RbohD in syncytia containing root segments than Col-0 plants (table S1). The total number of invaded nematodes and the average size of nematodes and syncytia were unchanged in 35S::RbohD compared to Col-0 plants 14 dai (Fig. 1, A to C). Although the expansion of the syncytia reached its maximum size at about 14 dai, female nematodes continued to grow up to 4 weeks after inoculation. At 25 dai, we found that female nematodes were larger in 35S::RbohD and smaller in rbohD or rbohD/F compared to Col-0 plants (Fig. 1D). Thus, RbohD is necessary but not sufficient to promote nematode invasion and growth and may be partially functionally redundant with RbohF in these processes.

To confirm the specificity of these observations, we used two complementary approaches. First, we used transgenic lines overexpressing RbohD in rbohD plants (35S::RbohD/rbohD). Unlike rbohD plants, 35S::RbohD/rbohD plants did not show significant differences in the number of invaded nematodes or in the size of female nematodes or syncytia compared to Col-0 plants (fig. S2, A to D), suggesting that 35S::RbohD complemented the rbohD mutation. Second, we treated plants with the compound diphenyliodonium (DPI), which inhibits Rboh activity (23, 24). Col-0 plants treated with DPI had fewer invaded nematodes 14 dai compared to untreated control plants (Fig. 1E), and both female nematodes and syncytia were smaller (table S2).

DPI is an inhibitor of multiple flavoenzymes and could be toxic to nematodes. However, we found that rearing Caenorhabditis elegans larvae on nematode growth medium supplemented with DPI did not affect the number of eggs laid after 3 days (fig. S3A), suggesting that DPI does not affect nematode development and sexual maturation. Moreover, we found that incubating J2 H. schachtii in DPI for 5 days (approximately the time required for J2 nematodes to molt into J3 in plants) before inoculation decreased their ability to infect Col-0 plants (fig. S3B), but this effect was smaller than that seen when plants were treated with DPI (Fig. 1E). In addition, the size of female nematodes and syncytia was unchanged in DPI pretreated compared to control H. schachtii nematodes

Fig. 1. Nematode infection assays in Rboh mutant, RbohD overexpressing, and DPI-treated plants. (A) Nematodes present in plant roots at 14 dai. Data points represent percent of nematodes where the number of nematodes per square centimeter of root area in Col-0 plants was set to 100%. (B) Average size of female nematodes 14 dai. (C) Average size of plant syncytia 14 dai. (D) Average size of female nematodes 25 dai. (E) Nematodes in DPI-treated plants 14 dai. Data points represent percent of nematodes where the number of nematodes per plant in Col-0 plants was set to 100%. For (A) to (E), data points represent three independent experiments (means ± SEM). Data were analyzed using single-factor analysis of variance (ANOVA) (P < 0.05). Asterisks indicate P < 0.05 compared to Col-0. Dunnett’s tests were used for post hoc analyses.
RbohD and rbohF plants had reduced infection by nematodes, we characterized this process in more detail. We addressed whether reduced infection was due to decreased initial attraction of nematodes to roots by quantifying the number of successful invasions at an earlier time point. At 2 dai, there was no difference in nematode invasions between Col-0 and rbohD or rbohD/F plants (Fig. 2A). We also asked whether nematode migration or development within the plant was impeded by Rboh deficiency. Through repeated observations of the same invasion sites, we found that more nematodes left their initial invasion site in rbohD/F compared to Col-0 plants (Fig. 2B). In addition, more invaded nematodes were dead at 7 dai or failed to undergo sexual differentiation by 10 dai in rbohD/F compared to Col-0 plants (Fig. 2B).

We assessed whether there could be defects in ISC establishment by monitoring for the cessation of stylet movements in nematodes that invaded roots 4 hours after inoculation (hai) and found that the average time to ISC establishment was increased in rbohD/F compared to Col-0 plants (Fig. 2C). Finally, we measured the growth of nematodes and syncytia after ISC establishment. We selected nematodes that successfully established an ISC at 2 dai to eliminate variability due to unsynchronized invasion and monitored their growth over 10 days. Both the nematodes (Fig. 2D) and syncytia (fig. S4) were significantly smaller by 3 dai and grew slower in rbohD/F compared to Col-0 plants. Thus, either RbohD or RbohF or both are required for nematode growth as well as ISC establishment and syncytium development, but not initial nematode invasion.

RbohD and RbohF are required for ROS production at early stages of nematode infection

Nematode infection triggers ROS production in plants (25). To identify whether RbohD and RbohF were required for this process in H. schachtii–infected roots, we visualized ROS with 3,3′-diaminobenzidine (DAB) (26) 1 dai. In the majority of Col-0 plants, DAB staining was increased at the site of nematode invasions (Fig. 3, A and B). However, the percent of invasion sites with increased DAB staining was reduced in rbohD or rbohF plants (Fig. 3, A, C, and D) and DPI-treated Col-0 plants (fig. S5) and eliminated in rbohD/F plants (Fig. 3, A and E). Overexpression of RbohD did not affect DAB staining in invaded roots (Fig. 3, A and F). Thus, RbohD and RbohF are required for ROS production during the initial stages of nematode infection.

To confirm the specificity of DAB-visualized ROS production, we labeled plants with 5-(and-6)-chloromethyl-2′,7′-dichlorodihydrofluorescein diacetate (CM-H$_2$DCFDA), which fluoresces when activated by ROS in living cells (27). We used confocal microscopy to monitor fluorescence in invaded roots of plants labeled with CM-H$_2$DCFDA 1 dai. We found that the extent of CM-H$_2$DCFDA fluorescence was increased in invaded roots of Col-0 (Fig. 3, G and H), but not rbohD/F; plants (Fig. 3I). Thus, during the early stages of nematode infection in plants, RbohD and RbohF produce ROS, which may support a biotrophic relationship.

RbohD and RbohF prevent cell death during syncytium formation

The delayed ISC selection by nematodes in rbohD and rbohD/F plants suggested that there could be anatomical changes in the roots that obstruct nematode migration. Using light and transmission electron microscopy, we examined cross sections of roots taken at the border of elongation and the root-hair zones associated with primary growth and at the lateral root formation zone associated with secondary thickening. The anatomy and growth of uninfected roots in both the primary (Fig. 4A) and secondary growth phases (fig. S6) were similar among Col-0 and Rboh mutant and overexpressing plants (28).

![Fig. 2. Nematode infection assays in Rboh mutant plants. (A) Nematode invasion at 2 dai. Data represent percent of nematodes where the number of inoculated nematodes was set to 100%. (B) Observation of nematode behavior and development for 10 dai. Data represent percent of nematodes where the number of invaded nematodes was set to 100%. Left root, 3 dai. Dead, 7 dai. Nondeveloped, 10 dai. (C) ISC selection time. (D) Average size of female nematodes over 10 dai. For (A) to (C), data points represent three independent experiments (means ± SEM). Asterisks indicate P < 0.05 compared to Col-0 (t test).](http://stke.sciencemag.org/ on August 17, 2021)
Fig. 3. Visualization of ROS in infected roots. (A) Quantification of DAB staining of ROS shown in (B) to (F). Data represent three independent experiments (means ± SEM). (B to F) DAB staining of ROS 1 dai on infected roots of plants with the indicated genotype. (G to I) CM-H$_2$DCFDA staining of ROS in living plant roots during migration (G and I) and ISC establishment (H). Scale bar, 50 μm. N, nematode.

To investigate structural changes in response to nematode infection, we analyzed cross sections of roots at 2, 5, and 14 dai. In Col-0, rbohF, and 35S::RbohD plants, we found little evidence of necrosis (Fig. 4, A and B, and fig. S6). In contrast, in rbohD and rbohD/F plants, we found necrosis as early as 2 dai (Fig. 4A). Ultrastructural analysis suggested that these cells were outside the range of the nematode stylet and had osmiophilic deteriorated protoplasts and thickened cell walls (Fig. 4B). Moreover, depositions of colllose-like material were present near cell walls neighboring necrotic cells (Fig. 4B). We found syncytia composed of several hypertrophied cells in Col-0, rbohF, and 35S::RbohD plants 2 dai, whereas rbohD or rbohD/F plants contained no syncytia or only the ISC (Fig. 4, A and B, and fig. S6). At 5 dai (Fig. 4, A and B, and fig. S7) and 14 dai (fig. S6), syncytia in rbohF or 35S::RbohD roots resembled those in Col-0. In contrast, the few syncytia found in rbohD or rbohD/F roots at these times were smaller and composed of fewer and less hypertrophied cells (Fig. 4, A and B, and figs. S6 and S7). These syncytia had more osmiophilic cytoplasm with plastids containing starch grains (Fig. 4B and fig. S7), and the syncytial cell walls were thin with few openings (Fig. 4B and fig. S7). In rbohD or rbohD/F roots at 5 and 14 dai, some syncytia showed signs of cellular degradation such as an osmiophilic and flocculent or translucent cytoplasm (fig. S7), whereas other syncytia showed no features of degradation but were smaller in size and composed of fewer hypertrophied cells (fig. S7). These observations suggest that ISC selection is hampered in rbohD or rbohD/F plants and that necrosis of syncytia can occur at multiple times during its formation.

To confirm that rbohD or rbohD/F show enhanced syncytial necrosis, we quantified cell death using fluorescein diacetate (FDA) (29). We found a significant decrease in FDA fluorescence intensity in rbohD/F compared to Col-0 plants at 6 hai and 2 dai (Fig. 5), both during the early migratory stages and when nematodes are establishing the ISC, respectively. Col-0 plants treated with DPI also showed a significant decrease in FDA fluorescence compared to control-treated plants (fig. S8). Thus, cell death is enhanced in the absence of Rboh after nematode infection, implying that ROS produced by RbohD or RbohF or both during nematode migration and ISC selection prevents the activation of the plant defense responses, leading to cell death and enabling nematodes to establish syncytial nurse cells.

**ROS limit cell death independent of SA**

NADPH oxidases antagonize SA-dependent death-inducing signals during the hypersensitive resistance response in *A. thaliana* (16). We used real-time polymerase chain reaction (PCR) to assess changes in the expression of genes that are increased by SA or jasmonic acid signaling, or antioxidant accumulation. By analyzing root sections containing female nematode-associated syncytia 10 dai, we found that the expression of the SA-responsive genes *PR1, PR2,* and *PR5* increased in *rbohDF* plants and that expression of *PR2* and *PR5* decreased in 35S::RbohD compared to Col-0 plants (Fig. 6). Uninfected roots of *rbohDF* and 35S::RbohD plants did not show detectable changes in the expression of *PR* genes compared to control (fig. S9). In contrast, the expression of genes that respond to jasmonic acid signaling and antioxidant accumulation were not consistently changed in *rbohDF* and 35S::RbohD plants (Fig. 6 and fig. S9). Thus, the reduced growth of nematodes in *rbohDF* plants could be due to the activation of local SA-mediated defense responses at infection sites.

To assess whether enhanced cell death in infected *rbohDF* plants was due to failure in activation of SA-dependent cell death signals, we focused on SID2, a protein in the isochorismate synthase pathway (30). Plants with *SID2* loss of function have basal SA but do not increase SA in response to infection (30). Thus, we predicted that mutation of *SID2* could increase nematode infection as well as nematode and syncytia size in *rbohDF* plants. We found that sid2 plants had more invaded nematodes relative to Col-0 plants at 14 dai (Fig. 7A), indicating that SID2-dependent SA is required to limit nematode infection. However, the size of female nematodes (Fig. 7B) and syncytia (Fig. 7C) did not differ between *sid2* and Col-0 plants, suggesting that SID2 does not interfere with syncytium development or nematode growth. In *rbohDF/sid2* triple-mutant plants (*rbohDF/sid2*), both the number of invaded nematodes (Fig. 7A) and the size of syncytia (Fig. 7C) were comparable to those of *rbohDF* plants. Moreover, the size of female nematodes was comparable in *rbohDF/sid2*, *sid2*, and Col-0 plants (Fig. 7B). Thus, the defect in nematode growth in *rbohDF* plants is likely independent of *SID2*-dependent SA, and the retarded growth of female nematodes in *rbohDF* plants could depend on SA-mediated defense responses.

We assessed whether SID2-dependent SA was required for enhanced cell death in *rbohDF* plants responding to nematode infection. If SID2 was required for nematode resistance in *rbohDF* plants, then we would expect to see that *rbohDF/sid2* plants had reduced cell death compared to *rbohDF* plants. *rbohDF/sid2* plants had a significant decrease in
the intensity of the FDA fluorescence at 6 hai compared to Col-0, but not rbohD/F, plants (Fig. 7D). These data support the model that the incompatibility of rbohD/F plants with the initial establishment of ISC is independent of SID2-dependent SA.

We found that loss of RbohD and RbohF increased the expression of SA-dependent genes in nematode-infected plants. To test whether SA was downstream of RbohD and RbohF, we assessed the expression of SA-dependent genes in rbohD/F/sid2 plants. The expression of PR1, PR2, and PR5 was at or below the limit of detection in infected root segments of rbohD/F/sid2 plants, despite normal amounts of 18S (table S4). Thus, we were not able to calculate a fold difference relative to Col-0 plants. Nevertheless, there was no qualitative evidence of a large increase in expression of PR1, PR2, and PR5 in rbohD/F/sid2 compared to Col-0 plants, suggesting that SA-dependent gene expression is inhibited downstream of RbohD and RbohF during nematode infection.

Fig. 4. Microscopic analysis of root anatomy and the development of nematode-induced syncytia in Rboh mutant and overexpressing plants. (A) Light microscopy micrographs of sections taken at root-hair zone of uninfected plants (left column) and at the nematode head region of infected roots 2 dai (middle column) or 5 dai (right column). Asterisks mark the nematode. Arrows indicate the position of primary xylem bundles. (B) Transmission electron microscopy micrographs of sections taken at nematode head region from 2 dai (left column) and 5 dai (right column) roots. Asterisks mark the nematode or the position of the nematode if the section was taken above its head or the head was located outside the field of view. Arrows point to cell wall stubs in syncytia. Triangles mark thickened cell walls. Arrowheads indicate callose deposits, and double arrowheads point to stylet insertion places. Ne, necrosis; S, syncytium; St, stylet; X, xylem vessel. Scale bars, 20 µm (A) and 5 µm (B).
DISCUSSION

Rapid production of ROS (oxidative bursts) in the apoplast by NADPH oxidases is an early defense response after the successful recognition of pathogens by the plant immune system (3, 6–8). Our analysis revealed that RbohD and RbohF are the main sources of host ROS produced during cyst nematode infections in A. thaliana. We predicted that host defense signals downstream of ROS would be inhibited by nematode-derived pathogenicity factors. However, we identified a previously uncharacterized function for RbohD- and RhobF-dependent ROS in facilitating nematode infection and feeding site development.

We propose that the infection of A. thaliana by H. schachtii proceeds in two phases: In the first phase, nematode invasion of roots and subsequent migration causes cellular damage that triggers cell death. NADPH oxidase-produced ROS disrupt the relay of death-inducing signals between the directly damaged and surrounding cells, thereby preventing the spread of cell death and supporting nematode infection. ROS also contribute to the process of ISC establishment. Thus, the increased cell death seen in rbohD/F plants (Figs. 4 and 5) could result from a failure of nematodes to establish syncytia. However, we found that cell death was increased in rbohD/F at the site of nematode invasion as early as 6 hai, when the nematodes were still in the migration phase (Fig. 5), suggesting that the failure of ISC establishment is not sufficient to explain all of the increased cell death in these plants.

Moreover, because we found that mutation of SID2 did not enhance nematode infection (Fig. 7A) or decrease early cell death in rbohD/F plants (Fig. 7D), we infer that this initial wave of increased cell death is independent of pathogen-induced SA signaling.

In the second phase of nematode infection, the establishment of the ISC and subsequent syncytium expansion is a prerequisite for biotrophic parasitism of the nematode. ROS signaling at infection site inactivates SA-mediated defense responses and enables the growth of nematodes. Consistent with this model, we found that female nematodes that were able to establish syncytia were significantly smaller in rbohD/F compared to Col-0 plants (Fig. 7B), but those in rbohD/F/sid2 plants were not (Fig. 7B). It is possible that the decreased nematode size results indirectly from increased plant cell death in rbohD/F plants.
which would reduce the number of cells available to be included in the syncytia.

Our model is compatible in part with previous findings showing that pathogen-induced ROS suppress the spread of SA-mediated cell death signals in plants after infection (16, 31). It was suggested that RbohD suppresses the spread of cell death by controlling the levels of antioxidants in cells at and around the infection site (16). In contrast, we found that the expression of antioxidant genes, glutathione reductase 1, catalase 1, and ascorbate peroxidase 1, did not change in rbohD/F roots with established syncytia. Thus, the role of Rbohs in the protection from SA-mediated cell death may not involve these genes.

This model raises the question of whether nematodes release factors that actively stimulate the formation of ROS. H. schachtii was found to secrete the effector protein 10A06 into host cells, which interacts with host spermidine synthase 2, leading to increased polyamine oxidase activity in syncytia (32). Increased polyamine oxidase may increase the production of ROS that serve as signaling molecules at low concentration for the development or function of syncytia (32).

Syncytium formation in host roots is accompanied by widespread transcriptional and metabolic changes in both the infected and systemic plant tissues (33, 34), and ROS could alter these changes. We found that RbohD and RbohF have the capacity to influence SA-dependent gene expression in infected roots. However, Rboh activity may play a broader role in syncytium development and function. Moreover, the fact that RbohD mediates systemic signaling in response to diverse stimuli (23) suggests that ROS could be involved in systemic signaling between nurse cells and the host plant.

Suppression of death-inducing signals by ROS in compatible biotrophic interactions is previously uncharacterized. Our results provide further understanding of the molecular mechanism that enables pathogens with destructive invasive behavior to switch to a biotrophic lifestyle, leading to the establishment of a long-term feeding relationship with the host plant, suggesting a process in the co-evolution of a nematode and host plant during which the parasite gains the ability to use NADPH oxidase–mediated cell death regulation to its own benefit.

**MATERIALS AND METHODS**

**Plant material and growth conditions**

*A. thaliana* plants were grown in petri dishes containing agar medium supplemented with modified Knop’s nutrient solutions under conditions described previously (35). The rboh mutants and 35S::RbohD strains have been described (3, 16). The Sid2 mutant strain was the allele sid2-2eds16-1 (30). rbohD/F/sid2 plants were generated by crossing and confirmed by PCR. The primers are listed in table S5.

**Nematode infection assays**

Nematodes were inoculated onto the surface of agar medium in petri dishes. For each experiment, 30 plants were used for each genotype. The number of male and female nematodes per plant was counted at 14 dai. Alternatively, the number of nematodes per square centimeter of root area was calculated for rbohD, rbohF, rbohD/F, or 35S::RbohD plants for the data shown in Fig. 1A to rule out the influence of root area on nematode infection. For the root area calculation, the plants were photographed with a DM2000 dissection microscope (Leica Microsystems) at the time of infection, and the area was calculated using Leica Application Suite (LAS) software (Leica Microsystems). The average size of syncytia and associated nematodes was measured in longitudinal optical sections as described previously (21). Briefly, 50 infection sites in roots containing syncytia and nematodes were photographed with a Leica DM2000 dissection microscope at 14 dai. The syncytia or females were outlined, and the area was calculated using LAS software (Leica Microsystems).

**DPI experiments**

For experiments with DPI, Col-0 plants were grown as described above. After 5 days, seedlings were transferred to petri dishes containing agar medium supplemented with DPI (1 µM) and used for nematode infection assays. In experiments designed to test the direct effect of DPI on *H. schachtii* invasion, freshly hatched J2 nematodes were incubated with DPI (1 µM) for 5 days at room temperature. Then, the nematodes were collected and resuspended in 0.7% (w/v) GelRite (Duchefa) containing DPI (1 µM) to ensure prolonged contact with DPI. For the *C. elegans* development experiments, nematodes were reared in nematode growth medium (36) supplemented with DPI at the indicated concentrations. Synchronized L1 larvae were obtained by sodium hypochloride treatment (36). Nematodes were fed *Escherichia coli* OP50. Egg lays were counted after 3 days from three replicates.
Nematode behavioral assays
For nematode invasion assays (Fig. 2A), the number of nematodes invading the roots at 2 dai was counted. To assess nematode migration, death, and sexual development (Fig. 2B), nematodes invading the roots 1 or 2 dai were selected (with permanent marker on the petri dishes), and their behavior was followed during the next 10 days by taking photographs every 24 hours. For each experiment, 20 nematodes were examined for each plant genotype. For ISC selection experiments (Fig. 2C), nematodes that were invading the root at 4 hai were marked with permanent marker on the petri dishes, and their styel movements were observed hourly for 16 hours. ISC selection was defined as the time when a nematode stopped styel movements. For each experiment, 20 to 30 nematodes were observed for each plant genotype. For the long-term growth experiments (Fig. 2D), nematodes that established ISC at 1 dai were marked with permanent marker on the petri dishes and imaged daily. For each experiment, 30 to 40 nematodes were examined for each plant genotype.

ROS detection
To visualize H$_2$O$_2$, a type of ROS, roots were stained with DAB using a modification of the protocol described in (28). At 1 dai, infected roots were incubated in DAB solution (1 mg/ml in water) at room temperature for 3 to 5 hours in a high-humidity box. The samples were then fixed in a solution of ethanol/lactic acid/glycerol (3:1:1). Root segments without lateral root primordia, mechanical stress, and root tips were selected for imaging with a Leica DM4000 microscope (Leica Microsystems) equipped with an Olympus C-5050 digital camera. The average number of stained spots was calculated for 50 nematodes per plant genotype. For CM-H$_2$DCFDA (C6827, Molecular Probes) staining, plants were grown on cover slips. At 1 dai, the agar was carefully removed from around root segments containing nematodes. Root segments were incubated with CM-H$_2$DCFDA (10 µM) in phosphate-buffered saline for 90 min at 4°C (3). After incubation, the samples were washed with KCl (0.1 mM) and CaCl$_2$ (0.1 mM) to remove excess CM-H$_2$DCFDA. The samples were kept at room temperature for 1 hour and then imaged with a Zeiss CLSM 710.

Cell viability labeling
Root segments were cut (0.5 cm) and transferred to half-strength Murashige and Skoog basal medium (MS medium, Sigma-Aldrich) containing FDA (5 µg/ml) (29). FDA stocks (2 mg/ml in acetone) were stored at −20°C. Root segments without lateral roots or root tips were used for staining. After 10 min of incubation, root segments were washed five times with MS medium without FDA. The fluorescence emission intensities were measured at 535 nm after excitation at 485 nm by using a microplate reader (Infinite 200 Pro, Tecan) (29). For each experiment, six root segments were used per plant genotype.

Microscopic analysis
Root segments were dissected, fixed, dehydrated, and embedded in epoxy resin as described previously (21). Light and transmission electron microscopy analyses were conducted on sections obtained from the same samples. Root segments were serially sectioned on an RM2165 microtome (Leica Microsystems) into 2-µm sections. Sections were collected on glass slides, stained with an aqueous solution of crystal violet dye (1%, Sigma-Aldrich), and imaged on an AX70 Provis (Olympus) light microscope equipped with an Olympus DP50 digital camera (Olympus). At selected places, ultrathin sections (90 nm) were taken for transmission electron microscopy with a UCT ultramicrotome (Leica). Ultrathin sections were stained with a saturated ethanol solution of uranyl acetate (Sigma-Aldrich) followed by lead citrate (Sigma-Aldrich) and imaged on an FEI 268D Morgagni transmission electron microscope (FEI Company) equipped with an SIS Morada digital camera (Olympus SIS). Digital images were adjusted for similar contrast and brightness, cropped, and resized using Adobe Photoshop software.

Real-time PCR
Root segments (up to 200) containing syncytia associated with female nematodes were dissected at 10 dai. Total RNA was extracted using a NucleoSpin RNA kit (Macherey-Nagel) according to the manufacturer’s instructions, including deoxyribonuclease digestion. Reverse transcription was performed with the High-Capacity cDNA Reverse Transcription Kit (Invitrogen) according to the manufacturer’s instructions. Quantitative PCR was performed with the Stepone Plus Real-Time PCR System (Applied Biosystems). Each sample contained 10 µl of Fast SYBR Green qPCR Master Mix with uracil-DNA, glycosylase, and 6-carboxy-x-rhodamine (Invitrogen), 2 mM MgCl$_2$, 0.5 µl each of forward and reverse primers (10 µM), 2 µl of complementary DNA (cDNA), and water in a 20-µl total reaction volume. The primers are listed in table S5. Samples were analyzed in three technical replicates. 18S was used as an internal control. Relative expression was calculated by the $\Delta\Delta$Ct method (37), where the expression of each gene was normalized to 18S and then to Col-0 to calculate fold change. The range shown in Fig. 6 was calculated from three experimental replicates (37).

SUPPLEMENTARY MATERIALS
www.sciencesignal.org/cgi/content/full/7/320/ra33/DC1
Fig. S1. Nematode infection assays in Rboh mutant plants.
Fig. S2. Nematode infection assays in 35S::RbohD mutant plants.
Fig. S3. Development and invasion of nematodes treated with DPI.
Fig. S4. Plant syncytium size in rbohD mutant plants.
Fig. S5. ROS visualization in roots of DPI-treated Col-0 plants.
Fig. S6. Light microscopy of uninfected Rboh mutant plants in secondary growth and infected Rboh mutant plants 14 dai.
Fig. S7. Transmission electron microscopy of Rboh mutant plants 5 and 14 dai.
Fig. S8. Cell viability in nematode-infected and uninfected plants treated with DPI.
Fig. S9. Analysis of gene expression in uninfected roots.
Table S1. Expression of Rboh genes in uninfected roots.
Table S2. Nematode and syncytium size in DPI-treated Col-0 plants 14 dai.
Table S3. Nematode and syncytium size in Col-0 plants 14 dai with nematodes preincubated with DPI.
Table S4. Expression of PR genes in Col-0 and rbohD/F/sid2 uninfected roots.
Table S5. Primers sequences used in this study.

REFERENCES AND NOTES

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Parasitic Worms Stimulate Host NADPH Oxidases to Produce Reactive Oxygen Species That Limit Plant Cell Death and Promote Infection

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Promoting Parasitism with ROS

Some species of nematode worms can invade the roots of plants and establish a feeding site composed of a large syncytial plant cell. This biotrophic lifestyle requires that the worms find a way to suppress plants’ immune responses. One aspect of plant immunity is the production of reactive oxygen species (ROS) that damage pathogens and promote plant cell death to limit the spread of infection. Siddique et al. found that deleting the enzymes that produce ROS in Arabidopsis thaliana plants responding to infection by Heterodera schachtii worms prevented the worms from establishing syncytia and growing within roots, suggesting that the worms have co-opted plant ROS as a means of promoting parasitism. Thus, plant ROS can play both positive and negative roles during infection.