High throughput virus-induced gene silencing implicates heat shock protein 90 in plant disease resistance

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Virus-induced gene silencing was used to assess the function of random Nicotiana benthamiana cDNAs in disease resistance. Out of 4992 cDNAs tested from a normalized library, there were 79 that suppressed a hypersensitive response (HR) associated with Pto-mediated resistance against Pseudomonas syringae. However, only six of these clones blocked the Pto-mediated suppression of P. syringae growth. The three clones giving the strongest loss of Pto resistance had inserts corresponding to HSP90 and also caused loss of Rx-mediated resistance against potato virus X and N-mediated tobacco mosaic virus resistance. The role of HSP90 as a cofactor of disease resistance is associated with stabilization of Rx protein levels and could be accounted for in part by SGT1 and other cofactors of disease resistance acting as co-chaperones. This approach illustrates the potential benefits and limitations of RNA silencing in forward screens of gene function in plants.

Keywords: gene silencing/HSP90/plant disease/resistance

Introduction

Plant viruses are activators of RNA silencing through a process that involves 21±25 nucleotide short interfering RNA (siRNA) (Hamilton and Baulcombe, 1999; Waterhouse et al., 2001). By analogy with findings from animals, it seems that the siRNA is processed from a double-stranded RNA (dsRNA) precursor by a DICER RNase III homologue and that it is incorporated as the specificity determinant into an RNA interference specificity complex (RISC) (Hannon, 2002). In virus-induced silencing, the dsRNA either is a viral replication intermediate or is produced by a host-encoded RNA polymerase using a viral RNA template (Mourrain et al., 2000). The viral RNA in this process is thus both an initiator and a target of the silencing mechanism. At the beginning of the infection cycle, the levels of dsRNA and siRNA would be correspondingly low and the viral RNA replication would be unchecked by silencing. However, at later stages of the cycle when viral dsRNA is more abundant, the higher levels would target RISC to the viral RNA and the rate of viral replication would slow down. Eventually the accumulation of viral RNA would stop or even decline.

Virus-induced RNA silencing, also referred to as virus-induced gene silencing (VIGS), is normally species-specific for viral rather than host RNA. However, if the viral genome is modified to include host sequences, the corresponding host RNAs are targeted and the symptoms in the infected plant resemble the phenotype of a null or reduced function mutant (Kumagai et al., 1995; Ruiz et al., 1998). This approach to suppression of host gene expression is useful in the assignment of gene function because it is fast (Baulcombe, 1999). The virus vector constructs can be assembled using standard DNA manipulations and, as symptoms develop in the infected plant by 7±21 days post-inoculation (d.p.i.), a loss-of-function phenotype can be produced within a month of having identified a gene of interest.

The use of VIGS for analysis of gene function has been validated by the use of virus vector constructs targeted against genes involved in primary and secondary metabolism, development and disease resistance (Atkinson et al., 1998; Kjemtrup et al., 1998; Jones et al., 1999; Burton et al., 2000; Ratcliffe et al., 2001; Jin et al., 2002; Liu et al., 2002a; Peart et al., 2002a; Slaymaker et al., 2002). Here we describe an application of VIGS in a forward screen of genes required for disease resistance. We produced a normalized library of Nicotiana benthamiana cDNA in a vector derived from potato virus X (PVX). This vector was in an Agrobacterium Ti plasmid so that Agrobacterium inoculation could be used as a high-throughput means of initiating virus infection without isolation and in vitro transcription of the PVX cDNA (Turpen et al., 1993). Plants were infected with individual PVX constructs from the library, and the resulting symptoms were used as a guide to the function of cloned cDNA. To identify cDNAs of genes involved in disease resistance, the infected plants were assayed for Pto-mediated resistance against P. syringae. We anticipated that silencing would lead to susceptibility to P. syringae if the target of VIGS encoded a protein that is, or is similar to, a cofactor of disease resistance.

The primary screen for Pto resistance was based on a hypersensitive cell death response that is elicited by the bacterial AvrPto protein in the presence of Pto (Rommens et al., 1995). Out of 4992 cDNAs that were silenced, there were 79 that affected the Pto-mediated hypersensitive response (HR), of which there were six that silenced genes required both for the HR and for the Pto-mediated hypersensitive response.
suppression of bacterial growth. Three of these PVX clones with the most pronounced effect on the Pto phenotype carried inserts corresponding to HSP90-like chaperonins encoded by a small multigene family. Silencing of these genes also compromised virus resistance mediated by the Rx and N proteins conferring resistance against PVX and tobacco mosaic virus (TMV), respectively. Thus, VIGS is an effective means of screening for novel gene function and is informative about multigene families that may not be readily accessible by mutagenesis because of functional redundancy. The HSP90 proteins may play a role either in stabilization of proteins involved in disease resistance or in assembly of multimeric complexes required for activation of R proteins and intracellular signalling.

Results

A cDNA library in PVX

A cDNA library for insertion into a PVX agroinfection vector (Figure 1, pGR106) was synthesized using polyadenylated RNA isolated from fully developed leaves of young N. benthamiana. The cDNA was normalized through three cycles of PCR to ensure that cDNAs of abundant mRNAs were not over-represented in the library. The abundance of clones representing rubisco, assessed by colony hybridization of aliquots of the library, was ~100-fold lower (1/600) than in an equivalent library of non-normalized cDNA (1/6). In contrast, rare mRNAs [phytoene desaturase (PDS) and PRF] were similarly abundant (~1/10 000) before and after normalization (data not shown).

After ligation of the normalized cDNA into the Ti plasmid PVX vectors and transformation into Agrobacterium, we confirmed that >95% of the colonies contained inserts of between 400 and 1000 bp in length. Each of 4992 PVX clones in Agrobacterium was then inoculated to a single 3 cm high N. benthamiana plant at the five-leaf stage. Nearly all (~95%) of the plants developed symptoms of virus infection that, in some instances, were similar to the normal mosaic associated with PVX. However, there were also plants with chlorosis, necrosis, leaf distortion or stunting (Figure 1B). These symptoms were present in many of the plants to some extent but, in ~15% of the plants, they were pronounced. Figure 1B illustrates examples of the most frequently observed symptoms. Presumably these symptoms were due to VIGS of endogenous genes.

Screening of genes required for Pto-mediated resistance

To find out whether genes required for Pto-mediated resistance were represented in the PVX library, we used an HR assay. AvrPto and Pto (Scal et al., 1996; Tang et al., 1996) were transiently expressed in leaves of the PVX vector-infected plant in the expectation that an HR would develop only in plants that were fully competent to carry out Pto-mediated resistance. Consistent with this expectation, there was an HR in the infiltrated regions of non-infected or PVX:green fluorescence protein (GFP)-infected plants (Figure 2A). Thus PVX did not interfere with the interaction of AvrPto and Pto or with the signalling pathway leading to the HR. In contrast, the HR did not develop if the plants were infected with a virus vector construct (PVX:PRF) that would silence the Prf cofactor of Pto-mediated resistance (Figure 2A) (Peart et al., 2002a). Therefore, the loss of the HR could be used as an indicator of genes that are required for Pto-mediated resistance.

Out of the 4992 PVX vector clones tested, there were 79 for which the silencing phenotype resulted in compromised AvrPto-induced HR. For each of these 79 clones, the loss of the HR was consistent in at least two replicate tests involving a minimum of three plants each.
In some instances, as with PVX:PRF, the loss of HR was complete (e.g. PVX:10-186 and PVX:9-037 shown in Figure 2A). However, there were other clones (e.g. PVX:8-240 shown in Figure 2A) that caused only partial suppression or delay of the HR. The GenBank accession numbers of the insert sequences are presented as Supplementary table 1 available at The EMBO Journal Online and on our website (www.sainsbury-laboratory.ac.uk).

To find out whether loss of the AvrPto-induced HR was accompanied by loss of disease resistance, Pto transgenic plants (line 38-12) (Rommens et al., 1995) were infiltrated with a dilute suspension (5 x 10⁴ c.f.u/ml) of P. syringae pv tabaci either without (Pst) or with AvrPto [Pst(AvrPto)]. In plants inoculated with Pst, the disease symptoms were manifested at 3 days post-inoculation as a water-soaked lesion in the infiltrated patch of the leaf. After a further 3 days, this lesion became necrotic and surrounded by a chlorotic halo. These symptoms developed irrespective of whether the plants were previously infected with PVX:GFP or PVX:PRF (Figure 2B). However, in the Pto transgenic plants infected with PVX:GFP, Pst(AvrPto) did not cause necrotic symptoms and the inoculated regions developed only a slight green chlorosis (Figure 2B). Presumably the lack of symptoms in these plants was due to the elicitation of the Pto-mediated resistance by AvrPto.

In the Pto transgenic plants that had been previously infected with PVX:PRF, the water-soaked lesions and subsequent necrosis due to Pst(AvrPto) were as severe as with Pst (Figure 2B). Similarly, with six out of the 79 PVX clones that suppressed the Pto-AvrPto-mediated HR, the Pto-mediated resistance was suppressed. With two of these clones (PVX:10-186 and PVX:9-037), the suppression of resistance was as effective as with PVX:PRF. The severe Pst symptoms developed within 4 d.p.i. (Figure 2B). However, with the other clones (PVX:8-240, PVX:8-320, PVX:11-9 and PVX:13-21), the Pst symptoms did not develop until 6 days or later or were milder than on PVX:PRF-infected plants (Figure 2B). We conclude that these six PVX clones contained inserts representing genes that are required for Pto-mediated disease resistance.

Two of the six clones (PVX:10-186 and PVX:9-037) contained chimeric inserts separated by AscI or NotI sites used in the original cDNA cloning process. For each of these chimeras, we produced derivative clones (PVX:10-186Apr and PVX:9-037-1) with single inserts that suppressed Pto-mediated resistance in exactly the same way as the progenitor. Further studies described below used these single insert clones.

To investigate the effect of these six clones on Pto resistance further, we measured bacterial growth in the virus-infected plants. In plants infected with PVX:GFP, the manifestation of Pto resistance was differential growth.
of *Pst* and *Pst(AvrPto)*: *Pst(AvrPto)* grew more slowly than *Pst* and, by 3 d.p.i., was 30-fold less abundant than *Pst* (Figure 3). As expected, in *Pto* plants infected with PVX:PRF, the loss of *Pto* resistance reduced the differential in growth of these strains. Similarly, following infection with PVX:10-186hsp, PVX:9-037-1 and PVX:8-240, the growth of *Pst(AvrPto)* was accelerated and both strains grew at similar rates (Figure 3). However, with PVX:8-320, PVX:11-9 and PVX:13-21, despite the delayed symptoms, there was differential growth of *Pst* and *Pst(AvrPto)* as in the PVX:GFP-infected plants (not shown).

To rule out that the loss of *Pto* resistance was an artefact associated with PVX, the 10-186hsp, 9-037-1 and 8-240 cDNA inserts were transferred into vectors based on tobacco rattle virus (TRV). These vectors were inoculated to *N.benthamiana* plants and, 3 weeks later, the plants were tested for the *Pto*-dependent HR and resistance against *Pst (AvrPto)*. In each instance, the results were the same as with the PVX vector: resistance and HR were compromised (R.Lu, unpublished data).

**Characterization of genes required for *Pto*-mediated resistance**

The PVX clones causing pronounced loss of *Pto* disease resistance (10-186hsp, 8-240 and 9-037-1) carried inserts of 549, 499 and 332 bp, respectively, that are similar to an *HSP90* cDNA from tomato (GenBank accession No. M86549) (Figure 4A and C). Correspondingly, the plants infected with PVX:10-186hsp and PVX:9-037-1 contained less HSP90 protein than the equivalent control plants (Figure 4B). From these results, it seems likely that the loss of disease resistance phenotype was due to VIGS of *HSP90*. The other three PVX clones causing loss of *Pto* disease resistance carried inserts corresponding to snRNA-associated proteins (8-320 and 11-9) or to proteins without known function (13-21) (Supplementary table 1). These clones have not yet been analysed in detail because there was weaker loss of disease resistance than with the *HSP90* clones.

The sequences of the 10-186hsp, 8-240 and 9-037-1 *HSP90* cDNAs were extended by RT±PCR (GenBank accession Nos AC310789, AC310781 and AC310776). These sequences clearly represent a gene family because they were non-identical in overlapping regions. To investigate the number of *HSP90* genes, we carried out RT±PCR of total cDNA with a primer from a conserved region that would have amplified cDNA of other *HSP90* homologues in addition to 10-186, 9-037-1 and 8-240. These RT±PCR cDNAs corresponded to the C-terminal 103 amino acids and the 3-non-coding region (see arrow in Figure 4A).

Most of the amplified cDNAs corresponded to the extended sequence of 10-186hsp or 8-240. However, there was an additional sequence (xy8) that was 2.9, 9.7 and 6.8% mismatched with the equivalent region of the 8-240, 9-037-1 and 10-186 cDNAs, respectively (Figure 4D). These four sequences were more similar to the cytoplasmic *HSP90* (Millioni and Hatzopoulos, 1997; Krishna and Gloor, 2001) of *Arabidopsis* than the organellar forms (Krishna and Gloor, 2001). However, these four *N.benthamiana* genes were more similar to each other than to any of the *Arabidopsis* *HSP90* s. It is likely, therefore, that the families of genes coding for cytoplasmic *HSP90* proteins in these two species evolved from a common gene ancestor through separate gene duplications. The functional difference of cytoplasmic and organellar *HSP90* is reinforced by the finding that a PVX clone targeted at an organellar *HSP90* (5-328) caused loss of *Pto*-mediated HR but had no effect on the *Pto* disease resistance (Supplementary table 1).

In addition to a role in disease resistance, it is likely that *HSP90* proteins have functions in plant growth and development. Consequently, with both the PVX and TRV vectors, there was a VIGS phenotype of stunting and leaf deformation (Figure 1D) that, as with the disease resistance phenotype, was more severe with 10-186 and 9-037-1 than 8-240. In some experiments, these symptoms eventually were so severe that the plants died.

**HSP90 is not specific for the *Pto* disease resistance pathway**

From genetic and biochemical analyses, it can be inferred that there are overlapping signal transduction pathways associated with different disease resistance genes (Innes, 1998). It was of interest, therefore, to find out whether
HSP90 silencing affected disease resistance associated with proteins with nucleotide-binding site and leucine-rich repeat domains (NBS-LRRs) encoded by the \( N \) and \( R_x \) genes. These proteins confer resistance against PVX (\( R_x \)) or TMV (\( N \)), and the experiments were carried out with \( N.benthamiana \) carrying either \( N \) or \( R_x \) transgenes (Bendahmane et al., 1999; Peart et al., 2002a). These plants were first infected with TRV:HSP90 and later challenge-inoculated with either PVX or TMV constructs that were modified to carry GFP reporter genes.

In \( N \) genotype plants infected with the TRV empty vector or with TRV:8-240, there was no detectable accumulation of TMV:GFP RNA (Figure 5A). However, following infection with TRV:10-186hsp or TRV:9-037-1, there was marked accumulation of TMV:GFP that could be monitored by northern analysis (Figure 5A). The level
of TMV accumulation was similar to that in plants infected with TRV:NRG1 in which the target of VIGS is required for N-mediated resistance (J. Peart and D.C. Baulcombe, unpublished). However, the loss of N-mediated resistance in TRV:HSP90-infected plants was incomplete because we could not detect systemic spread of the TMV:GFP. This partial loss of resistance is not intrinsic to the methods used because VIGS of SGT1 or N leads to loss of both local and systemic N-mediated resistance against TMV:GFP (Peart et al., 2002a,b).

Rx-mediated resistance against PVX was compromised in plants infected with TRV:9-037-1 and TRV:10-186hsp but not with TRV:8-240 (Figure 5B). This loss of Rx resistance was indicated by GFP fluorescence in the leaf inoculated with PVX:GFP or by northern analysis (Figure 5B) on Rx genotype N. benthamiana inoculated with PVX:GFP. However, the loss of Rx resistance was not as strong as in plants infected with TRV:Rx (Figure 5B) and did not allow systemic spread of PVX.

From these results, it seems that HSP90 is required for a process in disease resistance that is common to the three different disease resistance genes Pto, N and Rx. These three examples of disease resistance all involve NBS-LRR proteins: N and Rx both encode proteins in this class (Whitham et al., 1994; Bendahmane et al., 1999) and Pto resistance is dependent on the NBS-LRR product of Pfr (Salmeron et al., 1996). It was therefore of interest to monitor directly the effect of HSP90 VIGS on an NBS-LRR protein. To carry out this analysis, we used N. benthamiana carrying an Rx-4HA transgene. The haemagglutinin (HA) epitope-tagged protein conferred resistance against PVX as with the wild-type Rx (P.Moffett, unpublished data) and, despite its low level expression from the endogenous Rx promoter, was readily detectable by western blotting (Figure 6). After VIGS with the TRV:HSP90 constructs, the level of Rx-4HA was reduced (Figure 6) in parallel with the effects of these recombinant viruses on Rx disease resistance (Figure 5). Thus the 10-186 and 9-037-1 constructs caused a greater reduction of Rx-4HA than did TRV:8-240. In contrast, in plants infected with TRV:SGT1 in which Rx-mediated resistance was also suppressed, there was no detectable effect on the steady-state level of Rx-4HA (Figure 6). It seems, therefore, that the effect of HSP90 in disease resistance could be through direct or indirect effects on the accumulation of the NBS-LRR protein products of disease resistance genes. It also seems that HSP90 and SGT1 influence different stages of the Rx resistance mechanism.

**Discussion**

VIGS was developed as an alternative to insertional mutagenesis for analysis of gene function. It was proposed as an approach that would be informative about genes that could not be easily investigated by mutagenesis because they have a lethal phenotype (Baulcombe, 1999). In addition, it was intended to be more suitable than transgenic approaches with antisense or inverted repeat constructs for high throughput applications because the viral vector symptoms could be induced without the time-consuming and labour-intensive procedures for plant transformation. Here, by carrying out a survey of nearly 5000 cDNAs, we have validated the suitability of VIGS for high throughput analysis. Moreover, from the high frequency and nature of the extreme symptoms (Figure 1), we have indications that VIGS is informative about genes that are required for growth. Many of the VIGS targets, for example those producing stunted plants, would most probably have a lethal phenotype in a null insertion mutant. However, because the VIGS symptoms are established gradually on a fully developed plant, it is possible to differentiate ways of growth arrest that would not be straightforward in mutants with an embryo lethal phenotype. An additional hypothetical advantage of VIGS over insertional mutagenesis is the possibility of investigating genes in functionally redundant families. The discussion of VIGS and multigene families is included below in the assessment of the HSP90 gene family in disease resistance.

At present, VIGS has limitations. For example, it may not be a suitable approach for analysis of embryo and seedling characteristics or of genes expressed in fruit and seeds and, for reasons that we do not fully understand, it is more effective in N. benthamiana and related species than in other hosts. A further limitation of VIGS is the need for large-scale facilities for growing many plants under physical containment. However, it may be possible to miniaturize the procedures so that seedlings are agro-inoculated as they germinate and the VIGS symptoms are assayed in seedlings. Such developments will reduce the
time course, scale and expense of forward screens with VIGS. The use of vectors adapted for other hosts may also extend the applicability of VIGS forward screens (Holzberg et al., 2002; Liu et al., 2002b; Tumage et al., 2002).

A challenge for forward screens of gene function based on VIGS or other silencing approaches will be to ensure complete genome coverage. In the screen described here with 4992 cDNAs, if we conservatively assume 50% redundancy in the library and a genome size equivalent to a typical 25 000 genes, we would have covered ~10% of the transcriptome in our survey. To extend this coverage, we can simply test more clones. However, at some point, there would be a diminishing return and it would be necessary to target known expressed sequence tags (ESTs).

The role of the HR in disease resistance
Previous analyses of disease resistance in plants have concluded that the HR is secondary and not necessary for the suppression of the pathogen. For example, in Rx-mediated resistance against PVX, the HR was only induced if expression of the elicitor coat protein was uncoupled from virus replication (Bendahmane et al., 1999). It was concluded that the HR is a secondary mechanism that is activated only when the, as yet unidentified, primary mechanism failed to arrest the pathogen completely. The analyses of other resistance systems have come to the same conclusion. These systems involve the dnd1 mutant in Arabidopsis (Yu et al., 1998), the Sw-5-mediated resistance against Tospoviruses (Brommonschenkel et al., 2000), Rsvl-mediated virus resistance in soybean (Hajimorad and Hill, 2001) and resistance against cauliflower mosaic virus (Cole et al., 2001) in Nicotiana species.

If the HR is a secondary feature of disease resistance, it would be expected, as we found, that VIGS of some targets would not affect the mechanism leading to suppression of the pathogen but would interfere with the secondary cell death response. However, there was an unexpected high proportion of genes (73/79) with an HR-specific VIGS phenotype and no effect on pathogen growth. An explanation for this finding could be related to the number of components in the signal transduction pathways. If the part of the pathway affecting the growth of the pathogen involves fewer proteins than the HR branch, there would be correspondingly fewer VIGS targets. Alternatively, the HR part of the pathway may be affected by diverse VIGS targets that, perhaps including those that affect the general metabolic status of the cell, are not directly involved in disease resistance.

However, whatever the explanation, the discrepant results with the HR and disease resistance assays emphasize how these are very different tests. The HR...
test involves expression of the elicitor at a high level from the 35S promoter, whereas in the pathogen it would normally accumulate only at very low levels. The lesson for future VIGS screens is that direct tests of disease resistance are more useful than assays based on an HR.

The role of HSP90 proteins in disease resistance

HSP90 proteins facilitate protein folding, and it could be that NBS-LRR proteins or other components of the disease resistance pathways are dependent on HSP90 for correct folding, as in other systems (Nathan et al., 1997). The misfolded proteins could be either degraded or not biologically active. We cannot rule out this explanation. However, there are indications that HSP90 may be more specifically involved in disease resistance than is implied by a general role in protein folding. For example, there are mutations in HSP90 genes of Arabidopsis resulting in specific loss of disease resistance that do not lead to severe morphological phenotypes. One HSP90 mutation affects RPS2 (Takahashi et al., 2003), whereas another affects RPM1 (J. Dangl, personal communication). The findings that HSP90 interacts directly with proteins involved in disease resistance including SGT1 (Takahashi et al., 2003; J. Dangl, personal communication) are also an indication that this chaperonin has a specific role in disease resistance.

The VIGS phenotype of HSP90 is similar to that of SGT1 in that there is partial or complete loss of many disease resistance responses including those associated with Rx, N and Pto (Figures 3 and 6) (Peart et al., 2002b). Silencing of SGT1 and HSP90 were also similar in causing loss of non-host resistance against P. syringae pv. maculicola and in having no effect on non-host resistance against Xanthomonas campestris pv. campestris (I. Malcuit, unpublished data). These similarities may be significant because there are structural motifs that are common to SGT1 and HSP90-associated proteins known as co-chaperones. One co-chaperone of HSP90, p23, has sequence characteristics of the CS domain of SGT1 (Garcia-Ranea et al., 2002) that binds directly to the RAR1 disease resistance signalling protein. Other HSP90 co-chaperones including Hop have a tandem arrangement of three degenerate 34 amino acid repeats referred to as the tetracopeptide repeats (TPRs) that are also present in SGT1 (Azevedo et al., 2002). TPR domains bind specifically to the conserved C-terminal motif MEEVD of HSP90 (Chen et al., 1998; Yung et al., 1998).

A simple prediction, by extrapolation from these results, is that HSP90 would bind directly to SGT1 via the TPR domain. The bound SGT1 would then serve as a co-chaperone that could influence downstream signalling proteins through interactions of the CS domain. However, from the Rx-4HA accumulation data (Figure 6), we infer that HSP90 cannot only act in association with SGT1. HSP90 silencing results in reduced levels of Rx-4HA, whereas SGT1 silencing has no effect. Thus, there must also be an HSP90 effect at a level that is SGT1 independent and that affects the stability of Rx. This process may influence stability of other similar proteins because an HSP90 mutation in Arabidopsis causes destabilization of a disease resistance protein that, like Rx, has a nucleotide-binding site and leucine-rich repeat (J. Dangl, personal communication).

Does VIGS silence one or more members of the HSP90 multigene family?

VIGS can be effective with as few as 28 nucleotides of sequence identity between the insert in the virus vector and the target RNA (Thomas et al., 2001). It is therefore quite likely that the 9-037-1 and 10-186hsp inserts from the highly conserved coding sequence region would have silenced all HSP90 mRNAs. Consistent with this expectation, the western analysis showed almost complete absence of HSP90 in the tissues infected with the PVX vectors carrying these inserts (Figure 4B).

In contrast, the VIGS clones targeted at less divergent regions of the HSP90 mRNA had either weak or no suppression of disease resistance. For example, the 8-240 clone that corresponds to the 3′ region coding sequence and the untranslated region had only small and inconsistent effects on HSP90 protein levels and weaker effects than 9-037-1 or 10-168 on the various types of disease resistance (Figures 3 and 5) or on Rx levels (Figure 6). Similarly, PVX constructs with inserts from the 3′ untranslated regions of HSP90 mRNAs did not cause loss of disease resistance (9-295; Supplementary Table 1, and R. Lu, unpublished information). One interpretation of these results is that there is functional redundancy in the HSP90 gene family. However, we could not assess how efficiently these 3′-specific constructs had silenced the corresponding mRNA and formally we cannot rule out the possibility that there is functional differentiation of HSP90 isoforms.

HSP90 VIGS affected plant growth (Figure 1B) as well as disease resistance. The growth effects correlated with the effects on disease resistance in that 9-037-1 and 10-186hsp had more pronounced effects than 8-240. From this result, it could be concluded that HSP90 is involved in similar signalling pathways affecting normal plant growth and disease resistance. However, it could also be that HSP90 in plants, as in other eukaryotes, is required to chaperone correct folding of a subset of essential proteins (Nathan et al., 1997). Alternatively, as suggested recently, it could be that HSP90 is required to buffer cells against the epigenetic effects of misfolded proteins (Quitzsch et al., 2002). If that is the case, the growth phenotypes observed here (Figure 1D) could reflect the damage caused by the accumulation of misfolded proteins.

Materials and methods

Plant material

The plants were either non-transformed N. benthamiana or transgenic derivatives carrying Rx (line Rx18) and N (line 310A) and Pto (lines 38-12) (Rommens et al., 1995; Bendahmane et al., 1999; Peart et al., 2002a) as indicated in the text. The line Rx4HA-2 carrying an Rx-4HA construct was assembled by transformation with a modified version of pB1-RxHA (Bendahmane et al., 1999). The modification was the addition of three HA epitope tags (data not shown) to the 5′ end of the Rx opening reading frame in pB1-RxHA (Bendahmane et al., 1999). The resulting construct was used for Agrobacterium-mediated transformation of N. benthamiana and stable transformants were selected on kanamycin. The experiments shown were carried out in plants of line Rx4HA-2 that are homozygous for the Rx-4HA transgene and in which the PVX resistance was as strong as in lines transformed with wild-type Rx (P. Moffett unpublished data).

Viral constructs, virus inoculation and cDNA library construction

The TRV vector construct for agroinoculation (pTV00) and inoculation procedures have been described previously (Ratcliffe et al., 2001). The
PVX vector construct (pgR106) is a derivative of previously described clones (Chapman et al., 1992) (GenBank accession No. AY 297843). A similar vector with Clol, Smal and Sal sites for insertion of foreign sequence is also available (pgR107: GenBank accession No. AY 297842).

Inoculation procedures for the TRV vector were as described (Ratcliffe et al., 2001). With PVX constructs, we used a toothpick that was touched to an Agrobacterium colony and then used to pierce the leaf or petiole of a 2-3 cm high seedling. Systemic PVX infection developed after 5-10 days presumably because wounded cells were transfected with the Ti plasmid and were a source of infection for the rest of the plant.

Construction of the cDNA library in the PVX vector is described below. The PRF test was carried out as described by Chapman et al. (1992).

Total RNA for cDNA library construction was treated with RNase-free DNase (Promega), and recovered by ethanol precipitation. Reverse transcription used standard procedures, and cDNA normalization has been described previously (Ko, 1990; Kohchi et al., 1995). To facilitate cDNA amplification and subsequent cloning, a ‘lone’ linker, which is an annealing product of two primers Ascl A (5’-GAGATATAGGCGGCTACTA-3’) and Ascl B (5’-GAGATATAGGCGGCTATATA-3’), was added to both ends of all random cDNAs. Three rounds of normalization were performed consecutively. The normalized cDNAs were digested with Ascl and NotI, and cDNA fragments of 400 bp to 1 kb were purified, ligated into the PVX vector construct pgR106 and transformed into Agrobacterium GV3101 competent cells. To assess the efficiency of normalization, an aliquot of the ligation reaction was colony hybridization with probes specific for PRF and pgR.

PCR of HSP 90 sequences

Hsp90 cDNA sequences from N. benthamiana were amplified using the SMART cDNA RACE amplification kit (BD Bioscience-Clontech, Palo Alto, CA) with HSP90 gene-specific primer X (5’-GATATTCAATGCATTGAATGGGC-3’) and the library primer AP1. Nested PCR was performed with an HSP-speciﬁc nested primer Y (5’-TCTAGCATGGCTGGATACATGTCTAGCAAGA-3’) and nested primer AP2 according to the manufacturer’s instructions (BD Bioscience-Clontech). Both X and Y primers were designed from a region in the HSP90 sequence that is conserved in N. benthamiana, tomato and Arabidopsis cystoicolic Hsp90 sequences.

Monitoring of HR and bacterial and viral disease on plants

The HR test was carried out by infiltration of N. benthamiana upper leaves with a mixture of Agrobacterium cultures carrying 35S:Pto and 35S:AvrPto transgenes (Scott et al., 1996). Pseudomonas syringae pv. tomato (Pto) or Pseudomonas syringae pv. syringae (Pst) 11528 which is virulent on resistant tomato cultivars expressing Pto on Pto-transgenic N. benthamiana plants (Rommens et al., 1995). Pst 11528 (AvrPto) is a Pto AvrPto-expressing Pst transconjugant strain which is avirulent on resistant tomato cultivars expressing Pto and on Pto-transgenic N. benthamiana plants (Rommens et al., 1995). All Pst strains were grown in L medium only supplemented with 25 μg/ml kanamycin to maintain the transconjugation vector pDSK519 and 100 μg/ml rifampicin for the selection of Pst strains. Bacterial suspensions were inoculated onto leaves using a needleless syringe. Inoculation of diluted inocula [10,000 fold dilution from original cell suspension (OD600 = 1.0)] was used for disease symptom and bacterial growth assays. To measure in planta growth of Pst strains, three replicate samples, each containing leaf discs from three plants, were collected from infected leaves. Leaf discs were ground in 10 mM MgCl2, serially diluted and plated onto L medium containing kanamycin (25 μg/ml) and rifampicin (100 μg/ml). Colonies were counted after 24 h growth at 28 °C.

PVX:GFP and TMV:GFP derivatives were inoculated by infiltration or toothpick of Agrobacterium strains carrying the viral cDNA in Ti plasmid vectors, and RNA analysis was as described previously (Peart et al., 2002a). The probe used to detect TMV is the full-length GFP sequence. The full-length PVX coat protein sequence was used to be a probe for detection of PVX:GFP in the resistance assay test.

Protein analysis

For the analysis of the HSP90 protein, leaf samples were extracted in 50 mM Tris-HCl pH 7.5, 150 mM NaCl, 5 mM EDTA, 5 mM dithiothreitol (DTT), 1% Triton X-100, 1.5% polyvinylpyrrolidone supplemented with protease inhibitors (protease inhibitor cocktail for plant and tissue extracts, Sigma). A 50 μg aliquot of total protein was loaded onto a 6% SDS-polyacrylamide gel and, after electrophoresis, the gels were electroblotted onto PVDF membrane. Immunological reactions were carried with a primary antibody HSP90x (α-E-17), (Santa Cruz Biotechnology Inc., Santa Cruz, CA) which is an α-HA purified goat polyclonal antibody against a conserved peptide mapping near the N-terminus of HSP90x of Arabidopsis thaliana. For analysis of RX-4HA levels, the western blots were prepared and probed with anti-HA antibody (3F10, Roche) as described (Bendahmane et al., 2002).

Supplementary data

Supplementary data are available at The EMBO Journal Online.

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References


Note added in proof

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VIGS implicates HSP90 in plant disease resistance