Use of modified plum pox virus coat protein genes developed to limit heteroencapsidation-associated risks in transgenic plants

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Introduction

The coat protein (CP) gene was the first transgene successfully used to confer virus resistance to transgenic plants (Powell et al., 1986). Since then, numerous examples of genetically engineered, CP-mediated plant virus resistance (CPMR) have been reported in various systems (herbaceous and woody plants), and against at least 13 different groups of virus (Beachy et al., 1990; Wilson, 1993; Grumet, 1994). The ‘quasi-universal’ efficiency of CPMR and initial reports describing some interesting cases of broad spectrum resistance (Stark & Beachy, 1989; Nejidat & Beachy, 1990) have made this strategy very attractive for the creation of virus-resistant crops. In 1995, the first transgenic squash resistant to zucchini yellow mosaic virus (ZYMV) and watermelon mosaic virus II was approved for commercialization in the USA.

Although tremendous progress has been made during the last 5 years in understanding the mechanisms involved in the resistance of transgenic plants expressing viral CP genes (for recent reviews see Lomonossoff, 1995; Baulcombe, 1996), only a few studies have been concerned with the assessment and control of biological risks which may be associated with such plants. The large-scale use of these plants could theoretically lead to new ecological problems (de Zoeten, 1991; Tepfer, 1993). In particular, the presence of transgene products (RNA or protein) in the same cell as an infecting homologous or heterologous virus could modify the epidemiological characteristics of the virus. Three phenomena could be involved in this modification: recombination, synergism and heteroencapsidation (Robinson, 1996).

Heteroencapsidation has long been recognized in mixed infections involving different groups of aphid-borne viruses that are transmitted in a persistent, semi-persistent or non-persistent manner (Rochow, 1972; Murant et al., 1976; Simons, 1976). Exchange of capsid subunits between viruses of the...
same group can be responsible for the modification of vector specificity (Hu et al., 1988). In another case, a non-aphid-transmitted (NAT) strain became aphid-transmissible through phenotypic mixing (Bourdin & Lecooq, 1991).

Heteroencapsidation has also been observed between the CP produced in transgenic plants and the CP of incoming homologous or heterologous viruses (Osbourne et al., 1989; Farinelli et al., 1992; Lecooq et al., 1993). In the latter report, a ZYMV-NAT strain was transmitted by aphids when encapsidated with a plum pox virus (PPV) CP synthesized in transgenic Nicotiana benthamiana plants.

In view of these results, our goal is to produce transgenic plants which reduce the biological risks linked to heteroencapsidation. Newly modified PPV CP constructs were designed according to two strategies. The first was to remove the nucleotides coding for the DAG amino acid triplet involved in potyvirus aphid transmission (Atreya et al., 1990, 1991; Blanc et al., 1997). The new CP construct was designated ΔDAGCP (Jacquet et al., 1998). The second approach was to alter the CP transgene to obtain an encoded CP which would fail to assemble, thereby preventing possible heteroencapsidation in transgenic plants. A bacterial expression system was first used to check for the ability of the mutant CP to form virus-like particles (VLPs). The potential biosafety afforded by the use of modified PPV CP genes was then assessed in transgenic plants.

Methods

■ Modifications of the full-length PPV CP (FLCP) gene. The recombinant pBlueScript plasmid pTP3 contained the FLCP cDNA sequence (Ravelonandro et al., 1992). Deletion of nucleotides coding for the DAG amino acid triplet was achieved by PCR. Production of pΔDAGCP has been described previously (Jacquet et al., 1998). Two other plasmids, in which the nucleotides encoding R \( ^{238} \), Q \( ^{251} \) or D \( ^{341} \) were removed, were produced by site-directed mutagenesis as described by Kunkel et al. (1987). The mutagenic oligomers 5′-GCC AGA ATG TAG 3′ and 5′-GCC AAA CCC ACT TTT TTT CTA ACG 3′ and 5′-GCC AAA CCC ACT TTT CTT TTC AGC GAC G 3′ were used as primers to yield the pΔDAGCP and pΔQCP recombinant plasmids, respectively (asterisks in parentheses indicate the position of deleted triplets).

■ Cloning and expression of the different CP genes in E. coli. A high-level expression system (Qiagen) was used to express the different CP constructs in E. coli strain SG13009 (pREP4). BamHI and BglII restriction sites were inserted by PCR to flank each construct. Amplified fragments were then digested by these two enzymes and cloned in BamHI-BglII-digested pQE30 plasmid. The FLCP and modified PPV CP genes were thus unidirectionally cloned in the same frame as the ATG start codon of the vector. Moreover, a 6×His tag linked to the N-terminal part of each encoded protein can be used for protein purification. For each construct, three clones, verified by restriction mapping and sequencing, were tested by rapid screening of CP expression in small-scale (0.5 ml) cultures as described by the supplier. Three hours after induction with IPTG, cells were harvested by centrifugation and total soluble proteins were analysed on a 12% polyacrylamide gel (Laemmli, 1970). The highest expressing clone was selected for each construct.

■ Extraction of different induced proteins under native conditions. Following the manufacturer’s standard protein extraction protocol, most of the induced proteins were insoluble. A novel protocol was thus developed to increase the yield of non-denatured recombinant proteins. Important changes that improved the yield were the use of very low concentrations of IPTG for the induction and addition of 0.2% Sarkosyl in the lysis buffer (Jagadish et al., 1991; McNally et al., 1991). These two factors allowed us to make about 95% of the induced CPs soluble without apparently affecting their ability to polymerize into VLPs. In the modified protocol, 100 ml culture was centrifuged (5000 g, 15 min) 4 h after induction with 0.1 mM (final concentration) IPTG. The pellet was washed twice in 10 ml cold STE buffer (20% sucrose, 100 mM Tris pH 8, 10 mM EDTA) and resuspended in 5 ml of the same buffer containing 1 mg/ml lysozyme. The cells were then incubated for 20 min at 4°C and centrifuged again (5000 g, 10 min). The spheroplasts were suspended in 3 ml lysis buffer (100 mM Tris pH 8, 5 mM EDTA, 0.5 mM DTT, 0.5 mM PMSF, 0.2% Sarkosyl), gently shaken for 5 min and sonicated (three 10 s bursts in ice). RNase and DNase were added (1 µg/ml) for 20 min at room temperature before centrifugation (15 min, 11000 g). The supernatant was collected and centrifuged again, the pellet was discarded and the supernatant was concentrated in a Speed-Vac until the volume reached about 300 µl. Aliquots from these samples were used for electron microscopy analysis.

■ Immunosorbent electron microscopy. The procedure described by Bourdin & Lecooq (1991) was adapted for extracts from E. coli which were deposited on grids previously coated with a polyclonal PPV antiserum at a dilution of 1:3000. Immunosorbent electron microscopy studies on ZYMV-NAT-infected transgenic or non-transformed plants were conducted according to Lecooq et al. (1993).

■ Cloning in a binary vector and plant transformation. The insertion of FLCP and ΔDAGCP genes between a promoter sequence and the NOS terminator has been described previously (Ravelonandro et al., 1992; Jacquet et al., 1998). The other modified PPV CP gene (3ACP) contained deletions of the nucleotides encoding the DAG triplet, R \( ^{238} \), Q \( ^{251} \) and D \( ^{341} \). It was obtained by digesting the 5′ part of the ARQCP gene with BamHI and EcoRI and the 3′ part of the ΔDAGCP gene with EcoRI and Asp718. The fragments were then cloned into pBlueScript, previously digested with BamHI and Asp718. The 3ACP gene was then inserted between the 35S cauliflower mosaic virus promoter and the NOS terminator. This cassette was in turn excised and cloned between the HI–BglII restriction sites of the pBI301 recombinant plasmid (Ravelonandro et al., 1992). The resulting plasmid is designated pBI3ACP. Primary transformants were produced by leaf disk transformation with Agrobacterium tumefaciens strain LBA4404 (Horsch et al., 1985). A schematic representation of the different constructs is presented in Fig. 1.

■ Virus inoculation and detection. ZYMV-NAT does not readily systemically move in N. benthamiana (Gal-On et al., 1992). In order to increase the number of systemically infected plants, a first inoculation was performed on non-transformed N. benthamiana plants with sap extracts from infected ZYMV-NAT zucchini. The presence of the virus in newly formed leaves was verified 15 days post-inoculation (p.i.) by double-antibody sandwich (DAS)–ELISA. Systemic leaves from ELISA-positive plants were collected and ground in a citrate buffer (1:3; w/v), and this extract was then used as an inoculum on 4-week-old transgenic or non-transgenic N. benthamiana. The leaves found to be ZYMV-NAT positive by ELISA, at 15 days p.i., were used for ZYMV-NAT aphid-transmission.

■ Protein analysis. Accumulation of FL or modified PPV CP was evaluated by Western blot assay. Pellets from induced or non-induced SG13009 cells were suspended in lysis buffer (Laemmli, 1970). Young
Expression of modified PPV CP genes in plants

Results

Effect of CP structure on formation of VLPs

Bacteria were used to express FL and altered forms of PPV CP constructs and to study the effects of different amino acid deletions on the assembly of the CP into VLPs. The previously described FLCP and ΔDAGCP genes (Ravelonandro et al., 1992; Jacquet et al., 1998) and two newly modified PPV CP constructs (ΔRQCP and ΔDCP) were introduced into the expression plasmid pQE30 (Fig. 1). For ΔRQCP and ΔDCP nucleotides encoding the charged amino acids R^{220}, Q^{221} and D^{264}, located in the core of the PPV CP and shown to be involved in VLP formation of another potyvirus CP (Jagadish et al., 1993), were deleted.

 Cultures of E. coli transformed with pQFL, pQADAG, pQARQ or pQAD were induced with IPTG, and proteins were extracted and analysed by PAGE followed by Western blot. Fig. 2 shows the patterns of the different clones transformed with these plasmids. No extra band appeared in the pattern of induced SG13009 cells, which did not contain a pQE plasmid (lane 3). The PPV antiserum recognized bands of the expected size (36 kDa; Ravelonandro et al., 1992) for all four induced proteins (FLCP, ΔDAGCP, ΔRQCP and ΔDCP) (Fig. 2b, lanes 5, 7, 9 and 11).

Extraction of the induced proteins and electron microscopy observations

In order to observe assembly of the FL and of the modified PPV CP into VLPs, the proteins were extracted under non-denaturing conditions as described in the Methods; soluble protein extracts were concentrated and deposited on grids previously coated with a PPV antiserum. For each clone expressing the FLCP, ΔDAGCP, ΔRQCP and ΔDCP constructs,
10–20 grids were observed. Typical images are shown in Fig. 3. Flexuous PPV-like particles, 1–14 per grid square (Fig. 3a), were observed in the extracts prepared from FLCP and ΔDAGCP. These VLPs were highly heterogeneous in length (Fig. 3b) and were fully decorated by antiserum raised against PPV CP (Fig. 3d, e). VLPs were never observed on the 20 grids prepared with soluble protein extracts from induced cells containing the ΔRQCP and ΔDCP constructs.

**Selection of T2 lines to perform risk assessment**

A schematic representation of the different PPV CP constructs used to transform *N. benthamiana* is shown in Fig. 1. The production of pBIPCP and pBI35ΔDAGCP, containing constructs encoding the FLCP and ΔDAGCP, respectively, has been described previously (Ravelonandro *et al.*, 1992; Jacquet *et al.*, 1998). Another modified PPV CP construct with three
deletions of the nucleotides encoding the DAG and residues R225, Q226, and the D228 was produced as described in Methods. This plasmid was designated pB13ACP.

Following biochemical analysis and results of PPV resistance tests (Ravelonandro et al., 1993; Jacquet et al., 1998), T2 lines homozygously transformed with the FLCP, ΔDAGCP and 3ACP constructs were selected for further assessment according to two characteristics: the lines were (i) totally resistant to PPV (Jacquet et al., 1998; Ravelonandro et al., 1993) and (ii) high expressers of the transgene-derived products (to maximize potential risks such as transencapsidation or recombination with ZYMV-NAT products). Two lines per construct were selected according to these criteria. The accumulation of PPV CP in each of the selected lines is shown in Fig. 4. The FLCP accumulates to different levels in the BPC5 and BPC13 control lines (lanes 1 and 2). However, both lines displayed a recovery phenotype when infected with PPV (Ravelonandro et al., 1993) and were used by Lecoq et al. (1993) to demonstrate the risk of aphid transmission of ZYMV-NAT from FLCP transgenic plants. The ΔΔ2-4 and ΔΔ3-3 lines (lanes 3 and 4) were the highest expressers of the 3ACP gene among the PPV-resistant ΔΔ lines, producing protein at a level approximately similar to that observed in BPC5 plants. The accumulation of the ΔDAGCP was very high in the 35Δ4-1 and 35Δ6-19 lines (lanes 5 and 6).

Risk assessment studies

All the selected transgenic plants were inoculated with ZYMV-NAT, as described in Methods. ZYMV-NAT infection was confirmed in systemic leaves of the transgenic plants by DAS–ELISA. Surprisingly, the presence of the virus correlated with a significant increase in accumulation of the engineered FLCP or ΔDAGCP in most of the analysed BPC or 3Δ plants, whereas transcript-derived transgene levels were unchanged (not shown). Such a result was never observed in ZYMV-NAT-infected 3Δ plants.

Electron microscopy analysis performed with the samples prepared from BPC or 3Δ plants infected with ZYMV-NAT revealed the presence of three types of particle when PPV antiserum was used for decoration (Fig. 5). Some particles were not decorated at all but, in most cases, decoration could be observed along a portion of the particle. Fewer than 1% of the particles were totally decorated. This phenotypic mixing indicates that the ZYMV-NAT RNA was transencapsidated by the FLCP or the ΔDAGCP synthesized in transgenic plants. In contrast, observations of ZYMV-NAT-infected extracts from 3Δ plants revealed no evidence for phenotypic mixing. Indeed, no decoration of virus particles was detected with PPV antiserum (Fig. 6a), whereas the particles were fully decorated when ZYMV antiserum was used (Fig. 6b).

Aphid transmission tests with ZYMV-NAT were carried out with the infected transgenic plants as described by Lecoq et al. (1993), except that a higher number of aphids (15 or 50 instead of 10) was transferred onto each test plant (see Methods). Once the presence of the ZYMV-NAT was confirmed, aphids were allowed to acquire the virus from these plants, before being transferred onto the cucurbit test plants for the inoculation access period. Nine independent experiments were first performed, using 15 aphids on each cucurbit test plant. Table 1 shows that ZYMV-NAT was transmitted only from BPC plants, with a rate of transmission of 2%, regardless of the test plant used (melon or zucchini), except for the third experiment in which no transmission at all occurred. On the other hand, virus was never detected in more than 400 test plants following the transfer of the aphids from infected transgenic plants harbouring the modified ΔDAGCP and 3ACP. In another experiment (data not shown), a higher number of aphids (50) was used per test plant in order to increase the transmission potential. Again, ZYMV-NAT was transmitted only from BPC plants, with a calculated transmission rate of 33% (3/90 test plants infected). No transmission occurred from 35Δ- or 3Δ-infected plants (0/75 test plants infected in each case).

The 19 test plants in which ZYMV-NAT was transmitted by aphids were used individually in secondary aphid transmission experiments to 10 zucchini plants with 10 M. persicae per plant. No transmission occurred, confirming that these plants were infected by ZYMV-NAT, whereas such an experiment conducted with an aphid-transmissible ZYMV isolate led to 100% transmission (Lecoq et al., 1991).

Discussion

During the last decade, the CPMR strategy has been extensively studied and successfully used to produce virus-resistant transgenic plants (for reviews see Beachy et al., 1990;
Fig. 5. Phenotypic mixing observed in BPC (a) and in 35Δ (b) plants infected by ZYMV-NAT. Extracts from leaves used in the ZYMV-NAT aphid transmission assays were deposited on grids coated with a mixture of ZYMV and PPV antisera and were decorated with a PPV antiserum. Phenotypic mixing was observed in infected plants expressing the FLCP (a) and the ΔDAGCP (b). Bars, 200 nm.

Fig. 6. Lack of heteroencapsidated ZYMV-NAT particles in 3Δ plants. Each grid was coated with a mixture of ZYMV and PPV antisera. (a) No virus particles were decorated with PPV antiserum; (b) all particles were totally decorated with a ZYMV antiserum. Bars, 200 nm.
Table 1. Number of infected cucurbit test plants after aphid transmission of ZYMV-NAT from transgenic or non-transformed plants

BPC, 35A and 3A are transgenic plants expressing FLCP, ΔDAGCP or Δ3CP constructs, respectively. NT, Non-transformed plants. The presence of ZYMV-NAT in the source plants was tested by ELISA or Western blotting before each aphid transmission. Fifteen aphids were transferred onto each test plant. Zucchinis and melons were used as test plants in experiments 1–5 and 6–9, respectively.

<table>
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<th>4</th>
<th>5</th>
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<th>7</th>
<th>8</th>
<th>9</th>
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<td>1/80</td>
<td>3/100</td>
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<td>0/100</td>
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<td>0/80</td>
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<td>0/10</td>
<td>0/170</td>
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Grumet, 1994; Baulcombe, 1996). However, the use of such a transgene could lead to potential modification of an incoming virus which could then acquire new biological characteristics. The existence of such a risk has been demonstrated by Lecoq et al. (1993): a ZYMV-NAT isolate could be aphid-transmitted through heteroencapsidation with an engineered PPV CP synthesized in transformed plants.

In this work, strategies have been developed and evaluated which could be used to avoid the risks associated with heteroencapsidation, while still preserving the initial interest of the CP transgene, e.g. production of pathogen-derived resistance. To prevent undesired effects, nucleotides coding for amino acids involved in aphid transmission (the DAG triplet) or thought to be essential for the assembly of the PPV CP (R220, Q221 and D261) were deleted in these constructs. A prokaryotic system was first used to study the impact of the introduced deletions on the CP structure. Once produced in E. coli, the modified CPs were extracted under native conditions. VLPs, recognized by a PPV antiserum, were found in bacteria expressing the FLCP and ΔDAGCP genes. These observations are in agreement with the model proposed by Shukla et al. (1989) for the structure of the potyvirus CP, in that deletion of the N-terminal DAG triplet located on the surface of the particle did not affect the assembly of the CP subunits. However, VLPs were not observed in extracts from bacteria producing CPs with deletions of R220, Q221 or D261, indicating that the presence of these amino acids is essential for assembly of the PPV CP. These results are consistent with the observations of Jagadish et al. (1991, 1993), who used a similar system to test the effects of deletions or substitutions of equivalent amino acids in the Johnsongrass mosaic virus CP. Dolja et al. (1994) obtained similar results when using tobacco etch potyvirus infectious clones with amino acid substitutions of these charged amino acids. Results concerning the assembly of different CPs in E. coli are corroborated by in planta results, obtained by searching for the presence of phenotypic mixing in transgenic plants synthesizing the various CPs after infection with ZYMV-NAT. Thus, the FLCP and ΔDAGCP, which were able to assemble in bacteria, could also partially or totally heteroencapsidate the ZYMV-NAT RNA. Such a phenomenon was never observed with 3A CP, which failed to give VLPs in bacteria.

Western blot analysis following infection of transgenic BPC and 35A plants indicated that the presence of ZYMV-NAT was generally correlated with a visible increase in the accumulation of FLCP and ΔDAGCP. A similar increase in the accumulation of a transgenic potyvirus CP following potyvirus infection has already been reported in transgenic potatoes by Farinelli et al. (1992), who suggested that the effect could result from a better stabilization of the protein, linked to its incorporation into particles of the infecting potato virus Y strain N. Such an explanation could also apply to our observations in BPC and 35A plants, given that no increase of the 3A CP level was observed in transgenic plants following ZYMV-NAT infection (not shown). The detection of larger amounts of engineered CP in a transgenic plant in the presence of a heterologous potyvirus could thus represent additional evidence for the occurrence of phenotypic mixing.

This report confirms the results of Lecoq et al. (1993) showing that the PPV FLCP can complement the deficient ZYMV-NAT strain through heteroencapsidation. However, despite analysis of more than 400 test plants on which aphids were transferred from infected 35A or 3A plants, no ZYMV-NAT transmission was detected. These results thus show that the deletions introduced in the modified PPV CPs have allowed heteroencapsidation-associated risks to be controlled.

Although a large number of heteroencapsidated ZYMV-NAT particles were observed in the 35A plants, no aphid transmission occurred. This result confirms the recent demonstration that the DAG triplet, located in the amino part of the CP, is directly involved in potyvirus aphid transmission through interactions with the helper component (Blanc et al.,
A second DAG triplet is present in the PPV CP, as in some other potyviruses. As no complementation occurred with 35A plants, this second DAG is apparently not functional, probably due to its unexposed location in the CP. Newly modified PPV CP constructs have been produced to make the second DAG accessible. Transgenic plants expressing such constructs will be tested for aphid transmission of ZYMV-NAT to determine whether the second DAG can be rendered active.

Although recombination has been shown to occur between potyviruses (Revers et al., 1996) or between a transcript and a homologous incoming virus (Greene & Allison, 1994), the negative results obtained during secondary aphid transmission experiments suggest that no recombination has occurred between ZYMV-NAT RNA and PPV CP transcripts. Unlike other reports, in which recombination was described between a transgene-derived transcript and a viral RNA (Lommel & Xiong, 1991; Greene & Allison, 1994; Falk & Bruening, 1994), only a weak selection pressure was applied to ZYMV-NAT. Indeed, neither virus replication nor movement was blocked in the transgenic plants expressing PPV CP genes. These conditions could thus explain why no recombination was detected between the ZYMV-NAT RNA and the sequence encoding the DAG triplet from the FLCP transcripts.

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References


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