Gene Expression in Tobacco Low-Nicotine Mutants

Naruhiro Hibi, Shinji Higashiguchi, Takashi Hashimoto, and Yasuyuki Yamada

Department of Agricultural Chemistry, Faculty of Agriculture, Kyoto University, Sakyo-ku, Kyoto 606-01, Japan

Two nuclear genes, Nic1 and Nic2, regulate nicotine levels in tobacco. nic1 and nic2 are semidominant mutations in Burley 21 that reduce leaf nicotine levels and the activities of multiple enzymes in the nicotine pathway and simultaneously increase polyamine levels in cultured roots. Cultured roots homozygous for both mutations were used to isolate two cDNAs by subtraction hybridization; the transcript levels of these two cDNAs were much lower in the mutant roots than in the wild-type roots. The A411 gene encodes a 41-kD protein with considerable homology to mammalian spermidine synthase, whereas the A622 gene encodes a 35-kD protein with high homology to isoflavone reductase. When these genes were expressed in Escherichia coli, A411 had no spermidine synthase activity but did show putrescine N-methyltransferase activity, which is the first enzyme committed to the nicotine biosynthetic pathway, and A622 did not show isoflavone reductase activity. Both the methyltransferase and A622 genes are predominantly expressed in the root, and their expression levels in cultured roots are coordinate decreases by the nic mutations in the order of wild type > nic2 > nic1 > nic1 nic2. Removal of tobacco flower heads and young leaves rapidly and coordinate induced both genes in the root. Further, exogenous supply of auxin down-regulated both genes in cultured tobacco roots. These results suggest that Nic1 and Nic2 are regulatory genes for nicotine biosynthesis.

INTRODUCTION

Defined mutants are valuable tools in elucidating biosynthetic pathways and the regulation of secondary metabolite synthesis. In particular, genetic studies of flavonoid pigments have identified ~35 loci in petunia, ~12 loci in Antirrhinum, and ~10 loci in maize; these loci influence flavonoid biosynthesis (van Tunen and Mol, 1991). Most of these loci control only one step in the flavonoid biosynthetic pathway, and many have been identified as structural genes encoding biosynthetic enzymes. Some of the loci have been found to be regulatory genes that control multiple steps in the pathway and encode transcriptional factors (Dooner and Robbins, 1991). In contrast to current advances in our understanding of flavonoid biosynthesis, similar studies on other secondary products are limited. Because many secondary products are colorless, extensive screening programs by chemical analysis or pure luck is needed to identify rare mutants that display altered accumulation patterns of such invisible compounds (Hashimoto and Yamada, 1994).

Nicotine is the predominant alkaloid in most commercial varieties of tobacco. In the early 1930s, certain Cuban cigar varieties were found to have very low nicotine contents, and their low-alkaloid genes were subsequently incorporated into cigarette varieties through a series of backcrosses to meet the expected demand for low-nicotine cigarettes (Vialleau, 1949). LA Burley 21 was thus developed as a genetically stable breeding line with a very low-alkaloid content. This breeding line is not different from parental Burley 21 in days to flower, number of leaves, leaf size, and plant height, but is more susceptible to insect damage, probably due to its low nicotine content (Legg et al., 1970). Thorough genetic studies have demonstrated that the nicotine level is controlled by two non-linked loci (Legg et al., 1969). In this article, the two loci, originally called A and B, will be referred to as Nic1 and Nic2, respectively, and the mutant alleles in LA Burley 21 will be referred to as nic1 and nic2. nic1 and nic2 are semidominant and act synergistically. The dosage effect of nic1 on leaf nicotine levels is ~2.4 times stronger than that of nic2 (Legg and Collins, 1971).

Nicotine is synthesized in the tobacco root from ornithine and/or arginine by way of putrescine (Laete, 1980). Putrescine is either metabolized to higher polyamines, such as spermidine and spermine, or conjugated with cinnamic acid derivatives or fatty acids in all higher plants (Smith, 1981); it is also converted to N-methylputrescine in plants that produce nicotine or tropane alkaloids (Figure 1). Thus, putrescine N-methyltransferase (PMT; EC 2.1.1.53) participates in the first committed step in alkaloid biosynthesis (Hibi et al., 1992). N-Methylputrescine is then oxidized by a diamine oxidase (EC 1.4.3.6) and cyclized spontaneously to the 1-methyl-Δ1-pyrrolinium cation, which is condensed with nicotinic acid or its derivative by an unknown enzyme to form nicotine (Hashimoto and Yamada, 1993). Quinolinic acid phosphobutyrate transferase (QPT; EC 2.4.2.19) serves as the entry-point enzyme into the pyridine nucleotide cycle that supplies nicotinic acid (Wagner and Wagner, 1985).
Figure 1. Biosynthesis of Polyamines and Nicotine.

The diamine putrescine is metabolized to either polyamines or nicotine in tobacco. Spermidine synthase (SPDS) transfers the aminopropyl moiety of decarboxylated S-adenosylmethionine (dSAM) to putrescine, thus forming spermidine. In contrast, putrescine N-methyltransferase (PMT) transfers the methyl moiety of S-adenosylmethionine (SAM) to putrescine, thus forming N-methylputrescine, which serves as a precursor of nicotine.

RESULTS

Biochemical Characterization of Mutant Cultured Roots

Because nicotine is synthesized in the root, we established root cultures from four homozygous tobacco genotypes with Burley 21 background: wild type, nic1, nic2, and nic1 nic2. These cultured roots grew well in vitro, but the growth of nic1 nic2 roots was somewhat slower than that of the others (Table 1). Nicotine was the main alkaloid in the root cultures; nornicotine was the second most abundant alkaloid found. As much as 53% of nicotine and as much as 29% of nornicotine in the flasks were excreted into the culture media. The total alkaloid contents in the cultures are shown in Table 1. The combined contents of nicotine and nornicotine decreased stepwise in the order of wild type > nic2 > nic1 > nic1 nic2. The nornicotine content in the nic2 roots was significantly higher than that in the wild-type roots. Putrescine was the predominant polyamine in the wild-type cultured roots, followed by N-methylputrescine, spermidine, and spermine. These amines were present in both

The four genotypes of tobacco Burley 21 that have different Nic1 or Nic2 loci have been biochemically characterized to some extent. The activities of PMT and QPT in the root decrease in the order of wild type > nic2 > nic1 > nic1 nic2 as do the leaf nicotine contents of the respective genotypes, whereas the diamine oxidase activity in the root does not closely parallel the nicotine contents (Saunders and Bush, 1979). Several labeled nicotine precursors were incorporated into nicotine at reduced rates in hydroponically grown tobacco plants having nic1 or nic2 mutations (Hall, 1975). Apparently, multiple steps in nicotine biosynthesis are affected by the Nic loci. In this study, we employed differential screening to isolate genes that are under control of the Nic genes. In an analogous study, Martin et al. (1991) screened an Antirrhinum flower cDNA library for transcripts that differed in abundance between the wild type and the regulatory mutant del and identified previously uncloned biosynthetic genes in the flavonoid pathway that are regulated by Del. The two genes isolated in our study are regulated by Nic1 and Nic2: one encodes PMT, whereas the other may also be involved in nicotine biosynthesis.
bound, conjugated forms and the free, soluble form: typical proportions of the bound forms in total cellular amines were 90% for putrescine, 50% for N-methylputrescine, 76% for spermidine, and 51% for spermine in the cultured roots used. Total N-methylputrescine contents decreased in the order of wild type > nic2 > nic1 > nic1 nic2, whereas the total cellular contents of putrescine, spermidine, and spermine increased in contrast to the changes in the alkaloids and N-methylputrescine (Table 1).

These changes in the contents of nitrogen-containing compounds suggest that the metabolism of putrescine in the alkaloid pathway is blocked by mutations in Nic genes, resulting in the accumulation of putrescine and in an increased flow of metabolites into the polyamine pathway. This was supported by the measurement of PMT activity in cultured roots (Figure 2). PMT activity changed in proportion to the alkaloid contents in the root cultures. Therefore, the biochemical characterization of the mutant root cultures shown here confirms previous findings that nic1 affects nicotine biosynthesis more strongly than nic2 and that nic1 and nic2 act synergistically (Legg and Collins, 1971).

Two Classes of Transcripts Are Underrepresented in nic1 nic2 Roots

To identify genes that are regulated by the Nic loci, we looked for transcripts that were considerably less abundant in nic1 nic2 roots than in wild-type roots. A cDNA library of ~10⁴ clones was constructed from wild-type cultured roots and screened with both a subtracted cDNA probe enriched in wild-type specific sequences and a nonsubtracted cDNA probe from nic1 nic2 roots. A total of 11 clones that hybridized consistently to the subtracted probe but not to the nic1 nic2 probe was obtained. After analysis by cross-hybridization, these clones were classified into two groups in which A477 and A622 were the longest cDNAs. To gain insight into possible biochemical functions of the two cDNA groups, the sequences of A477 and A622 were determined.

A411 Is Homologous to Spermidine Synthase

A411 is 1395 bp long and contains one long open reading frame that encodes a polypeptide of 375 amino acids with a molecular weight of 41,084. The predicted protein has a very hydrophilic N terminus of ~80 amino acid residues; the N terminus contains four repeats of the heptapeptide Asn-Gly-His (or Tyr)-Gln-Asn-Gly-Thr and a total of six potential N-glycosylation sites (Figure 3). A search of the GenBank database revealed similarity to spermidine synthase (SPDS; Figure 4). Over almost the entire length of the synthase, identity and homology (including conservative amino acid replacements) were 49 and 73% similar to human SPDS (Wahlfors et al., 1990), 46 and 70%

Table 1. Growth and Metabolite Contents in Cultured Tobacco Roots

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Growth (mg dry weight)</th>
<th>Alkaloids (nmol/mg dry weight)</th>
<th>Polyamines (nmol/mg dry weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Nicotine</td>
<td>Nornicotine</td>
</tr>
<tr>
<td>Wild Type</td>
<td>235 ± 24*</td>
<td>120 ± 15</td>
<td>5.1 ± 1.1</td>
</tr>
<tr>
<td>nic2</td>
<td>225 ± 28</td>
<td>52 ± 8</td>
<td>31.9 ± 6.0</td>
</tr>
<tr>
<td>nic1</td>
<td>238 ± 27</td>
<td>39 ± 6</td>
<td>1.6 ± 0.4</td>
</tr>
<tr>
<td>nic1 nic2</td>
<td>195 ± 14</td>
<td>24 ± 4</td>
<td>1.1 ± 0.4</td>
</tr>
</tbody>
</table>

* Cultured roots of four tobacco genotypes (~60 mg dry weight of tissue) were grown in a liquid culture medium for 2 weeks in five replicates.
A477 cDNA sequence is D28506. Tapeptide are underlined, and putative N-glycosylation sites are marked as the putative translational start site. Four repeats of the related hep-

The nucleotide sequence is numbered from the 5' end of the cDNA clone.

were found in A411, as well as in SPDS (region I to V in Figure 8). It is interesting to note that the hydrophilic N-terminal extension is unique to A411 and is not present in any of the three SPDSs.

A411 Encodes PMT

SPDS transfers the aminopropyl moiety of decarboxylated SAM (dSAM) to putrescine, whereas PMT transfers the methyl moiety of SAM to putrescine (Figure 1). In addition, studies on substrate specificity and inhibition kinetics by amines have predicted that SPDS (Shirahata et al., 1991) and PMT (Hibi et al., 1992) may have similar active sites for enzyme catalysis. Therefore, we examined the possibility that A411 may encode SPDS, PMT, or both (i.e., bifunctional enzyme). The A411 cDNA was cloned into a pET-based vector to give pET411 so that an intact A411 protein would be expressed under the strong T7 promoter after induction by isopropyl β-d-thiogalacto-pyranoside. The enzyme activities of SPDS and PMT were measured in crude protein preparations from bacteria. As a host bacterial strain, we used an E. coli deletion mutant HT551 that lacks the SPDS gene (Tabor et al., 1986) and does not show either of the enzyme activities (Figure 5A). When the E. coli SPDS gene cloned in pSPD19 was expressed in HT551, we detected SPDS activity but not PMT activity (Figure 5B). However, when the A411 cDNA was expressed, only PMT activity was detected (Figure 5C). Therefore, we concluded that A411 encodes PMT, but not SPDS.

A622 Is Homologous to Isoflavone Reductase

A622 is 1179 bp long and contains one long open reading frame that encodes a polypeptide of 310 amino acids with a molecular weight of 34,648 (Figure 6). A search of the GenBank database revealed that A622 is similar to isoflavone reductase (IFR) over the entire length (Figure 7). Identity and homology were 58 and 79% similar to alfalfa IFR (Paiva et al., 1991) and 56 and 80% similar to chick-pea IFR (Tiemann et al., 1991). The A622 cDNA was expressed as an intact, soluble protein in E. coli, as with the expression of A411, and IFR activity was measured using 2'-hydroxyformononetin as a substrate. However, we could not detect any activity in cell extracts from the transformed bacteria; IFR activity was clearly detectable in the control extract from bacteria transformed with pIFRAlf, which encodes alfalfa IFR (Paiva et al., 1991) (data not shown). Thus, A622 probably encodes a reductase, but not IFR.

Genomic DNA Gel Blot Analysis

Genomic DNA from tobacco and Nicotiana sylvestris, one of the two progenitor species, was cleaved with BamHI, EcoRI, or KpnI, separated by agarose gel, and blotted onto nylon membranes. Blots were probed with 32P-labeled PMT cDNA (Figure 8A) or A622 cDNA (Figure 8B), both of which detected similar to mouse SPDS (DBJ accession No. L19311), and 31 and 58% similar to Escherichia coli SPDS (Tabor and Tabor, 1987). Amino acid sequences similar to the proposed binding motifs for S-adenosylmethionine (SAM) (Bugos et al., 1991) were found in A411, as well as in SPDS (region I to V in Figure 4). It is interesting to note that the hydrophilic N-terminal extension is unique to A411 and is not present in any of the three SPDSs.
Figure 4. A411 Is Homologous to SPDS.

Identical amino acid residues are indicated by asterisks, and identical and similar amino acid residues are shaded. Structurally similar amino acids are grouped as follows: M, L, I, V, C; F; W, Y, H; A, G, S, T, P; D, E, N, Q; and R, K, H. Gaps introduced to optimize the alignment are shown by dashes. An arrowhead indicates a putative amino acid change that might be important in differentiating between the enzyme reactions of PMT and SPDS (see Discussion). Proposed binding regions for SAM and dSAM are also shown.

two to five strongly hybridized fragments in the two genomes. The A622 probe also detected a few faintly hybridized DNA fragments only in the tobacco genome (arrowheads in Figure 8B). The tobacco genome contained a few extra fragments of the PMT gene in addition to those corresponding to the fragments in the N. sylvestris genome, whereas the tobacco fragments of the A622 gene all had counterparts in the N. sylvestris genome. if we take into account one polymorphism detected with EcoRI digestion (asterisks). These results indicated that the PMT gene is represented by at least two more highly homologous DNA sequences in the tobacco genome and that the A622 gene is probably a unique sequence in the tobacco genome derived from N. sylvestris. Thus far, we have been unable to detect any restriction fragment length polymorphisms for Burley 21 tobacco and the nicl nic2 mutant by using either cDNA probes, indicating that the PMT and A622 genes in the mutant are not grossly different from those in the wild type (data not shown).

PMT and A622 mRNA Levels Are Coordinately Regulated

Steady state levels of PMT and A622 transcripts in cultured tobacco roots were analyzed (Figure 9). As a positive control, a probe for the β-ATPase gene (Boutry and Chua, 1985) was
expression levels of PMT and A622 than the nic2 mutation and that strong synergistic effects exist between the two mutant alleles.

Both the PMT and A622 mRNAs were abundant in roots and were absent, or present at only very low levels, in stems and leaves of Burley 21 tobacco (Figure 10). In nic1 nic2 tobacco, both transcripts were similarly detectable only in roots, but at levels much lower than those in wild-type roots.

**PMT and A622 mRNA Levels Are Down-Regulated by Auxin**

Removal of the flower head and several young leaves causes a profound physiological adjustment in tobacco plants. This

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**Figure 5. A411 Encodes PMT, But Not SPDS.**

Crude enzyme preparations from E. coli cells that harbored the indicated plasmid were analyzed for SPDS and PMT. The products from the enzyme reactions are shown by arrows on the HPLC chromatograms.

(A) Host E. coli strain HT551.  
(B) E. coli cells transformed with pSPD19 expressing E. coli SPDS.  
(C) E. coli cells transformed with pET411 expressing A411. MP, N-methylputrescine.

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**Figure 6. Nucleotide and Deduced Amino Acid Sequences of A622 cDNA Clone.**

The nucleotide sequence is numbered from the 5' end of the cDNA clone. The first methionine of the open reading frame is designated as the putative translational start site. The DDBJ/EMBL/GenBank accession number of the A622 cDNA sequence is D28505.
A622 tobacco MVYeedKTIEITLGFTGyYIKYlyWLYTSAKSCHTFTLRE * * * * * * * * * * * 40
IFR alfalfa M--AFRENKILILGFTGAIHrniYAMGHTYALVREIKTPGNCVYKPL * 48
IFR chick-pea M--ASQNRILIILGFTGAIHrniYAMGHTYALIIRTGDIN5KPSLV * * * * * * * * * * * * * * * * * 48

A622 tobacco TLKNFR-5七EIDPSGyYQVLT2PQDSNHQYKIFKVVQGQV * 89
IFR alfalfa TANFFKETILWWGDGQVDKIVGDDKTVLDYVIVCNAKEL * 98
IFR chick-pea IAAAFKEEKLQSFKAQVILGDGMDNQVAKIQVYTVIcyFGL * 98

Tobacco Low-Nicotine Mutants 729

Figure 7. A622 is Homologous to IFR.

Homology was compared as indicated in Figure 4. Amino acid residues that are proposed to interact with NAD(H) or NADP(H) are shown by closed circles.

practice is common among tobacco growers and eliminates apical dominance as well as increasing root growth and nicotine content (Akehurst, 1981). It has been previously shown that PMT enzyme activity and nicotine content in the root increase severalfold 1 day after decapitation (Mizusaki et al., 1973). Figure 11 shows that the level of PMT mRNA increased within 30 min after decapitation, peaked after 1 hr, and declined thereafter. Similar changes in the level of A622 mRNA were also observed after decapitation. The maximum induction levels were approximately twofold for PMT and threefold for A622 over the nondecapitated control at 1 hr.

Because auxin synthesized in young expanding leaves is transported down the stem (Phillips, 1975), removal of the tip region may cause a reduced auxin supply from the aerial parts into the root, which may result in activation or derepression of structural genes involved in nicotine biosynthesis. Therefore, we examined whether auxin in the culture medium affects expression of the PMT and A622 genes in wild-type cultured tobacco roots (Figure 12). When cultured roots that had been grown in a medium containing 3 μM indolebutyric acid (IBA) were transferred into an auxin-free medium, both the PMT and A622 mRNA levels increased in less than 30 min, peaked at 1 hr, and slowly increased thereafter: the addition of IBA (3 μM) to the culture after 20 hr caused a rapid decrease in both transcripts. These results indicated that the PMT and A622 genes are down-regulated by auxin.

Discussion

PMT Has Evolved from Spermidine Synthase

The amino acid sequence of PMT, except for its unique N-terminal extension, is highly homologous to the sequences of SPDS from mammals and E. coli. Although plant SPDS genes have not been reported, we found that PMT is even more homologous to the peptide fragment (73% identity and 88% homology in 66 amino acid residues) encoded by a partial cDNA sequence of rice (GenBank accession No. D15401) that
Figure 8. DNA Gel Blot Analysis.
Genomic DNA (20 μg) from tobacco (Nt) and N. sylvestris (Ns) was digested with either BamHI, EcoRI, or KpnI, electrophoresed on 0.8% agarose gels, and transferred to nylon membranes. Molecular length markers are given at left in kilobases.
(A) The blot was probed with the PMT cDNA.
(B) The blot was probed with the A622 cDNA. Faintly hybridized DNA fragments are shown by arrowheads. Asterisks indicate DNA fragments that differ between the two genomes.

Figure 9. Transcript Levels of PMT and A622 Are Down-Regulated in nic Mutants.
RNA gel blots were made from total RNA (20 μg per lane) from cultured roots of four tobacco genotypes and were successively probed with PMT, A622, and β-ATPase cDNAs. Molecular lengths of the respective transcripts are given on the right in kilobases.
way to change the orientation of the methyl group would be to rotate the methyl group around the sulfur atom of the cofactor toward the amino group of putrescine. This might be accomplished by the above amino acid mutation that was introduced to bind the carboxyl group of SAM. The N-terminal hydrophilic extension unique to PMT might also be important in determining the reaction specificity of PMT. Alternatively, this N-terminal extension might be used to target PMT protein to a specific subcellular organelle, such as the alkaloid vesicle involved in biosynthesis of isoquinoline alkaloids (Amann et al., 1986), although the structure of the N terminus of PMT does not resemble that of any known signal peptide, and alkaloid vesicles have not been found that are specific for nicotine biosynthesis. Cloning of SPDS genes from tobacco and PMT genes from other alkaloid-producing species, in combination with protein engineering, should give further insight into the molecular evolution of PMT.

Because PMT is the first enzyme committed to the nicotine pathway, it is reasonable to assume that its expression is closely correlated with nicotine formation in tobacco. Reciprocal grafting experiments between tobacco and non-nicotine-producing species have suggested that nicotine is synthesized in the root and translocated, probably through xylem, to the aerial parts (reviewed in Tso, 1972). Accordingly, PMT enzyme activity is detected only in the root of tobacco plants (Mizusaki et al., 1971). Root-specific expression of the PMT gene (Figure 10) further confirms the site of nicotine synthesis in tobacco. Down-regulation of the PMT gene by auxin also reflects the inhibitory effects of auxin on nicotine formation in tobacco callus (Ohta et al., 1978; Feth et al., 1986).

A622 Is Homologous to IFR

A622 is highly homologous to IFR over its entire length, but did not show IFR enzyme activity when expressed in E. coli. Because IFR is specifically involved in the biosynthesis of isoflavonoid phytoalexins in the Leguminosae and because tobacco apparently does not use isoflavonoid phytoalexins in its response to fungal attack (Dixon et al., 1983), tobacco is not expected to have an IFR gene. The very high similarity between the A622 gene and the IFR gene indicates that these genes diverged relatively recently and that the A622 gene codes for an oxidoreductase that utilizes NADP(H) or NAD(H) as a cofactor. Possibly, the substrate for A622 may be structurally related to isoflavonoids. Similar to the PMT gene, the A622 gene is specifically expressed in the root, controlled by the Nic genes, and down-regulated by auxin, which suggests that it may be a structural gene for the biosynthetic pathway of nicotine or related alkaloids. The enzyme activity of QPT, the first enzyme in the biosynthesis of nicotinic acid, has been reported to be low in the root of the nic1 nic2 mutant (Saunders and Bush, 1979). However, because QPT requires 5-phosphoribosyl-1-pyrophosphate but not nicotinamide as a cofactor, it is an unlikely candidate for A622.

One step that involves reduction of a double bond in the nicotine pathway is condensation between the 1-methyl-Δ1-pyrrolinium cation and nicotinic acid, which forms nicotine. This is based on a feeding experiment using tobacco plants in which hydrogen from C-6 of nicotinic acid is lost during its incorporation into nicotine (Leete and Liu, 1973). Although detection of weak "nicotine synthase" activity in tobacco root extract was

![Figure 10. PMT and A622 Are Expressed in the Root.](image)

Total RNA was extracted from leaf, stem, and root of wild-type and nic1 nic2 tobacco and was used as described in the legend to Figure 9.

regulation of the PMT gene by auxin also reflects the inhibitory effects of auxin on nicotine formation in tobacco callus (Ohta et al., 1978; Feth et al., 1986).

![Figure 11. Decapitation Transiently Increases Transcript Levels of PMT and A622.](image)

Total RNA was extracted from roots of three wild-type plants at the indicated time after decapitation and was used after pooling as described in the legend to Figure 9. Control plants were not decapitated.
be several DNA sequences that are homologous to IFR but do not necessarily encode proteins with the same function.

**Nic1 and Nic2 May Be Regulatory Genes for Nicotine Biosynthesis.**

Enzyme activities of PMT and QPT (Saunders and Bush, 1979) and transcript levels of PMT and A622 are simultaneously reduced by either of the two mutations. Both mutations caused a decrease in PMT activity and a concomitant increase in polyamine contents, indicating that putrescine formation from arginine and ornithine is much less affected than nicotine synthesis by the Nic genes. These results indicate that multiple biosynthetic enzymes in the nicotine pathway are affected in each nic mutant and that the Nic genes may be regulatory genes that act specifically, or primarily, on nicotine biosynthesis. The semidominant phenotype of nic1 and nic2 (Legg and Collins, 1971) further suggests that Nic1 and Nic2 limit the regulation of the nicotine pathway.

Strong synergistic effects were observed between the nic1 allele and the nic2 allele, judging from their effects on the transcript levels of PMT and A622. The synergy between the two
mutant alleles may be explained by postulating that Nic1 and Nic2 perform the same function in regulating target genes (i.e., PMT, A622, and probably several other genes). The most probable case is that Nic1 and Nic2 are duplicate genes, each originating from one of the two tobacco progenitors. The stronger allele nic1 might be a null mutation, whereas the weaker nic2 allele might be a non-null mutation with residual Nic function. In this case, a mutation at one of the two Nic genes would reduce Nic function to no less than half of the wild type, whereas a double mutation would severely affect Nic function. Further molecular characterization, including cloning of the Nic loci, is necessary to elucidate their functions.

METHODS

Plant Materials

Seeds of four Burley 21 tobacco lines (germ plasms HPB21, HIB21, L1B21, and LAB21) were obtained from the U.S. Department of Agriculture (Beltsville, MD). These lines were isogenic, except for the two low-nicotine loci, and had genotypes of Nic1/Nic1 Nic2/Nic2, Nic1/Nic1 nic2/nic2, nic1/nic1 Nic2/nic2, and nic1/nic1 nic2/nic2, which had been previously referred to as AABB, AAbb, aaBB, and aabb, respectively (Legg and Collins, 1971).

Sterile seedlings of the four genotypes were grown in light on half-strength auxin-free BS medium (Gamborg et al., 1968) supplemented with 1.5% (w/v) sucrose and 1% (w/v) agar. Seedling roots were excised and transferred to HF medium (Mano et al., 1989), supplemented with 3% (w/v) sucrose and 3 μM indolebutyric acid (IBA), and cultured in the dark on a rotary shaker at 90 rpm. Two weeks after subculture, the cultured roots were harvested, immediately frozen with liquid nitrogen, and kept at −80°C until use. In one experiment, the cultured roots were rinsed well with HF medium without auxin and transferred to the auxin-free medium. Twenty hours after the transfer, filter-sterilized IBA solution was added to the culture medium to a final concentration of 3 μM.

Tobacco plants were grown from seed in soil for a month and transferred to pots containing a nutrient solution described by Takahashi and Yoshida (1957). Six plants were hydroponically grown in aerated nutrient solution in a greenhouse for 3 months, during which they developed ~10 flowers or flower buds. Flower heads and several young leaves were then removed from three plants, leaving 16 leaves on each plant. A portion of the roots were harvested from each plant after indicated intervals and pooled for RNA extraction. Three control plants were not decapitated.

Alkaloid and Polyamine Analyses

Nicotine and nornicotine were analyzed by gas liquid chromatography as described previously (Hibi et al., 1992), except that the column temperature was held at 120°C for 8 min and then increased from 120 to 250°C at a rate of 8°C/min.

Polyamines were first divided into water-soluble, trichloroacetic acid–soluble, and trichloroacetic acid–insoluble forms, and each form was quantified separately by HPLC after converting it to dansyl derivatives (Hibi et al., 1992).

RNA Isolation and cDNA Synthesis

Total RNA was extracted from plant tissues as described by Mohnen et al. (1985). Poly(A)+ RNA (5 μg) was purified from total RNA of cultured roots of wild-type and nic1 nic2 mutant tobacco lines using an mRNA purification kit (Pharmacia), and the purified RNA was used to construct double-stranded cDNA for the subtracted cDNA probes, using cDNA Synthesis System Plus (Amersham). A phagemid cDNA library was constructed from the wild-type poly(A)+ RNA using a Librarian II kit (Invitrogen, San Diego, CA).

Differential Screening

Subtractive hybridization was performed essentially as described by Wang and Brown (1991). Briefly, double-stranded cDNAs made from wild-type and mutant roots were fragmented and ligated to linkers for polymerase chain reaction amplification. Excess mutant cDNA was biotinylated and hybridized with wild-type cDNA, after which DNA fragments common to both cDNA pools were removed by binding to streptavidin and extraction with organic solvent. One subtraction cycle consisted of long (20 hr) and short (2 hr) hybridization steps. After one cycle, the subtracted cDNA pool was amplified by polymerase chain reaction, and the subtraction cycle was repeated two more times to yield the subtracted cDNA probe. A more detailed description of this procedure is provided elsewhere (Hashimoto et al., 1993).

Duplicate filters made from the wild-type cDNA library were hybridized separately with the subtracted probe and the nonsubtracted cDNA probe from the mutant root in 50% formamide, 5 × SSC (1 × SSC is 0.15 M NaCl, 0.015 M sodium citrate), 20 mM sodium phosphate, 5 mM EDTA, 0.1% SDS, and 100 μg/mL sonicated salmon sperm DNA at 42°C for 16 hr and then washed twice with 0.2 × SSC, 0.1% SDS at 42°C for 15 min and twice with the same buffer at 65°C for 30 min. DNA probes were radiolabeled by random hexamer priming. Clones that hybridized strongly to the subtracted probe and weakly, or not at all, to the mutant probe were chosen and further screened by dot blot hybridization. Eleven clones were confirmed to be positive and were classified into two groups based on cross-hybridization between them.

Nucleotide sequences of the cDNA inserts of the representative clones were determined on both strands using an ALF I DNA sequencer (Pharmacia) and a DNA polymerase sequencing kit (Pharmacia).

RNA and DNA Gel Blot Analyses

For RNA gel blot analysis, 20 μg of total RNA was electrophoresed on 1% formaldehyde agarose gels, blotted onto GeneScreen Plus membranes (Du Pont), and hybridized with the indicated radiolabeled probes at 42°C for 20 hr as described for differential screening. Whole cDNA inserts were used for the putrescine N-methyltransferase (PMT), A622, and β-ATPase probes. The levels of hybridization signals were quantified by the Radiometric Imaging System (AMBIS Systems, San Diego, CA). For normalizing the sample loading on each lane, the levels of PMT and A622 mRNAs were divided by the level of β-ATPase mRNA.

Total genomic DNA was isolated from tobacco leaves (variety Burley 21) as described by Murray and Thompson (1980), and 20 μg of genomic
DNA was digested with restriction enzymes, followed by electrophoresis on 0.8% agarose gels. The gels were subsequently denatured and neutralized by standard procedures (Meinkoth and Wahl, 1984). Subsequent procedures were performed as described above.

Expression in *Escherichia coli*

An Ncol site was introduced at the first ATG of the A411 and A622 cDNA inserts in pCDNA II using a Transformer site-directed mutagenesis kit (Clontech, Palo Alto, CA). Ncol-SamHI fragments containing A411 and A622 coding sequences were excised and cloned into pET-3d (Novagen, Madison, WI) to give pET411 and pET622, respectively. pET411 was introduced into A622. An Ncol site was introduced at the first ATG of A477 and expression in *Escherichia coli* was prepared as described for A411.

Expression of the homogenate at 22,000 g for 15 min, the supernatant was added to the culture and incubation continued at 16°C overnight. After 1 hr, M1W7 phage (8 × 10^10 plaque-forming units) isopropyl β-D-thiogalactopyranoside (IPTG) at 37°C until the OD₆₀₀ of the culture reached 0.5, when isopropyl β-D-thiogalactopyranoside was added to a final concentration of 1 mM. After 1 hr M1377 phage (8 × 10⁶ plaque-forming units) was added to the culture and incubation continued at 16°C overnight. Bacterial cells were then recovered by centrifugation, suspended in 100 mM potassium phosphate buffer, pH 7.5, 0.5% sodium ascorbate, 5 mM EDTA, and 5 mM DTT, and sonicated for 1 min. After centrifugation of the homogenate at 22,000g for 15 min, the supernatant was passed through a PD-10 column (Pharmacia), from which the desalted crude enzyme was eluted with 50 mM Tris-HCl, pH 7.5, 1 mM EDTA, and 1 mM DTT. E. coli HT573, which contains pSPD19 (Tabor and Tabor, 1986), was used as a source of spermidine synthase (SPDS). pET622 was introduced to *E. coli* BL21(DE3). The recombinant bacteria were cultured, and the recombinant A622 protein was expressed according to the method of Studier et al. (1990). Crude enzyme solution was prepared as described for A411.

Enzyme Assays

PMT activity was measured by HPLC as described previously (Hibi et al., 1992). For the assay of SPDS, the S-adenosylmethionine (SAM) component in the PMT assay mixture was replaced with decarboxylated SAM (dSAM). The reaction product spermidine was converted to the dansyl derivative and quantified by HPLC, as described previously (Hibi et al., 1992). Enzyme reactions were carried out at 30°C for 60 min using 68 µg of crude protein. Isoflavone reductase (IFR) activity was measured according to Paiva et al. (1991).

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