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The *Arabidopsis* homeotic genes *APETALA3* and *PISTILLATA* are sufficient to provide the B class organ identity function

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**SUMMARY**

The class B organ identity genes, *APETALA3* and *PISTILLATA*, are required to specify petal and stamen identity in the *Arabidopsis* flower. We show here that the activities of these two genes are sufficient to specify petals and stamens in flowers, in combination with the class A and C genes, respectively. Flowers of plants constitutively expressing both *PISTILLATA* and *APETALA3* under the control of the 3SS promoter from cauliflower mosaic virus consist of two outer whorls of petals and inner whorls of stamens. These plants also exhibit vegetative phenotypes that are not present in either of the singly (*APETALA3* or *PISTILLATA*) overexpressing lines. These phenotypes include leaf curling and the partial conversion of later-arising cauline leaves to petals. The presence of additional floral whorls in flowers ectopically expressing *APETALA3* and *PISTILLATA* and the rescue of missing organs in class A mutants by ectopic B function suggest that *APETALA3* and *PISTILLATA* play an additional role in proliferation of the floral meristem.

Key words: *Arabidopsis*, flower development, MADS box, *APETALA3*, *PISTILLATA*

**INTRODUCTION**

A wild-type *Arabidopsis thaliana* flower consists of four organ types that are arranged spatially in four concentric whorls. The organ type that develops in a particular whorl has been proposed to result from the activity of three different classes of organ identity genes (the ABC model) (Bowman et al., 1991; Coen and Meyerowitz, 1991; Meyerowitz et al., 1991; reviewed in Weigel and Meyerowitz, 1994). The combination of class A genes (including *APETALA1*; *AP1* and *APETALA2*; *AP2*), class B genes (including *APETALA3*; *AP3* and *PISTILLATA*; *PI*) and class C genes (including *AGAMOUS*; *AG*) that are active in each whorl determines the identity of the organs that will later develop in that whorl. The outermost whorl of sepals is specified by A activity, the second whorl petals are specified by the combination of A and B activities, the third whorl stamens are specified by the combination of B and C activities, and the fourth whorl carpels are specified by C activity. Two additional postulates of the model are that the A and C functions repress each other, such that a mutation in either of these functions results in the expansion of the other function into all four floral whorls, and that the A, B and C activities are capable of functioning in all whorls of the flower.

All five of these organ identity genes have now been cloned, and four of them *AP1*, *AP3*, *PI* and *AG* belong to the MADS box family of transcription factors. Consistent with their proposed activities, these four genes are expressed in spatially restricted domains (Yanoisky et al., 1990; Jack et al., 1992; Mandel et al., 1992b; Goto and Meyerowitz, 1994). The fifth organ identity gene, *AP2*, is a member of another family of proteins that share a domain (the AP2 domain), which has been shown to bind DNA in other members of this family (Jofuku et al., 1994; Weigel, 1995). *AP2* is expressed throughout floral and vegetative tissues (Jofuku et al., 1994).

Although each of these genes is clearly required for the specification of floral organs, the ABC model does not address whether they will be sufficient to specify a particular organ. Ectopic expression of *AG* (p35S-AG) has shown that this gene is sufficient to repress A function in the outer two floral whorls (Mandel et al., 1992a; Mizukami and Ma, 1992). Flowers of these plants contain carpelloid first whorl organs and staminoid or missing second whorl organs; flowers which closely resemble *ap2* mutants. Flowers of plants ectopically expressing *AP3* exhibit a partial conversion of fourth whorl carpels to stamens (Jack et al., 1994). Ectopic expression of *AP3* results in the persistent fourth whorl expression of the endogenous *PI* gene, and an active fourth whorl B function.

In this paper we show that ectopic expression of both class B genes together (p35S-PI p35S-AP3) results in flowers containing two outer whorls of petals and inner whorls of stamens, demonstrating that the activities of these two genes together are sufficient to provide B function. These plants also exhibit vegetative phenotypes including early flowering and leaf curling which are not found when either *AP3* or *PI* is ectopically expressed alone. The lack of any vegetative phenotype in either of the singly overexpressing lines results from the posttranscriptional regulation of *AP3* (Jack et al., 1994) and perhaps a similar posttranscriptional regulation of *PI*. Surprisingly, the ectopic expression of *AP3* and *PI* causes some of the later cauline leaves produced by the inflorescence to become petaloid. That the rosette leaves and early
cauline leaves do not undergo this transformation suggests that there may be a gradient of floral character in the plant. Ectopic B function also results in the formation of extra whorls of stamens in the center of the flower and restores the initiation of second whorl primordia which are missing in strong ap1 and ap2 mutants. These results reveal a role for the Arabidopsis B class genes in the proliferation of the floral meristem.

MATERIALS AND METHODS

Construction of p35S-PI

BamHI linkers were ligated to a 960 bp EcoRI/KpnI PI cDNA fragment (Goto and Meyerowitz, 1994). This piece of DNA was cloned into the BamHI site of pCGN18 (constructed by Leslie Sieburth). pCGN18 contains a 1.6 kb fragment of the 35S promoter and a 1.2 kb fragment of 3′ NOS cloned into the HindIII/BamHI and BamHI/KpnI sites respectively of pCGN1547 (McBride and Summelfelt, 1990).

Scanning electron microscopy

Samples were fixed, dried, coated and dissected as described previously (Bowman et al., 1989, 1991). The images were photographed on Kodak TMAX film.

In situ hybridization

Flowers were fixed, embedded, sectioned, hybridized and washed as described previously (Drews et al., 1991) except that the tissue was fixed for only 1-2 hours. AP3 and PI antisense probes were made by digestion of pD793 and pcPINX (Jack et al., 1994; Goto and Meyerowitz, 1994).

Immunolocalization

Flowers were fixed, embedded, sectioned and incubated as described previously (Jack et al., 1994).

GUS staining

Flowers containing pAP3-GUS (Jack et al., 1994) were stained for β-glucuronidase in a protocol adapted from Jefferson et al. (1987). The tissue was fixed for 15 minutes on ice with cold 90% acetone. The tissue was rinsed with 50 mM phosphate buffer pH 7.2 containing 0.5 mM K3Fe(CN)6 and 0.5 mM K4Fe(CN)6 and was subsequently incubated in 2 mM X-gluc in the above rinse solution for several hours at 37°C. The tissue was embedded and sectioned similarly to tissue prepared for in situ hybridization and was observed under dark-field illumination. Tissue for whole mounts was stained by incubating in 2 mM X-gluc overnight at 37°C.

Strain constructions

p35S-PI p35S-AP3 plants were crossed to various mutants by manual cross-pollination using homozygous mutant strains, except for ag-3 and sup-1 (for which heterozygous parents were used). The resulting p35S-PI p35S-AP3 F1 plants were crossed again to homozygous (or heterozygous in the case of ag-3 and sup-1) mutant strains. Triples (p35S-PI p35S-AP3 and the mutant) were identified in the F2. The presence of both p35S lines could be detected (in almost all cases) by the curled leaf phenotype. The presence of the mutant in the doubly transgenic lines was confirmed by crossing of F2 plants to homozygous mutants and/or sequencing (or digestion) of PCR reactions of leaf tissue (Klimyk et al., 1993) that amplified the relevant gene.

RESULTS

Floral phenotype resulting from ectopic expression of PI

Flowers of plants ectopically expressing PI (p35S-PI) show a partial first whorl conversion of sepals to petals (Fig. 1, compare A with B). The first whorl organs of p35S-PI are mosaic organs with both sepal and petal tissue. Cells at the base and margins of the organ are characteristic of petals while cells in the upper central region of the organ are characteristic of sepals. The partial first whorl transformation conferred by ectopic expression of PI is similar to that reported for ectopic expression of the Petunia class B gene, GREEN PETAL (Halter et al., 1994).

Floral phenotype resulting from ectopic expression of PI and AP3

Plants ectopically expressing both class B genes were generated by crossing plants containing the p35S-AP3 construct (Jack et al., 1994) to p35S-PI plants. Flowers of these plants (p35S-PI p35S-AP3) have two outer whorls of petals and inner whorls of stamens (Figs 1C, 2E, compare with wild type, Figs 1A, 2A). These first and fourth whorl transformations are more complete than the corresponding partial transformations exhibited by p35S-PI (first whorl) or p35S-AP3 (fourth whorl). The first whorl petals of p35S-PI p35S-AP3 have no sepal tissue (Fig. 2F-G compare with wild type B,C). However, stomata, which are not found on wild-type petals, are occasionally present on these petals. The primordia of the first and second whorl organs arise as in wild type, with the second whorl primordia arising later in development, interior and alternate with the first whorl petals (Fig. 2J). The third whorl usually consists of six stamens, with additional whorls of stamens located interior to this whorl (Fig. 2K). Only rarely is carpelloid tissue present in these inner whorls (Fig. 2L). The average number of stamens in p35S-PI p35S-AP3 is 15.6 (flowers 1-20 counted on five plants, with a range from 11-23) and is greater than that found in flowers homozygous for the p35S-AP3 construct (9.1) (Jack et al., 1994). The number of stamens decreases slightly in an acropetal manner such that the average stamen number in the first five flowers is 17.5 while that in flowers 16-20 is 14.8.

The first whorl organs of p35S-PI p35S-AP3 are noticeably different from wild type by stage 8 (stages according to Smyth et al., 1990), when the surfaces of these organs consist of cells of similar shapes and sizes, while the epidermal cells of wild type show more irregularity in shape and size (Fig. 2H compare with wild type, D). The longer epidermal cells found in these wild-type flowers are the probable progenitors of the elongate cells characteristic of sepals (Bowman, 1994). The fourth whorl of p35S-PI p35S-AP3 flowers is morphologically indistinguishable from wild type at stage 6. At this developmental stage in wild type, a central dome of cells is visible in the middle of the flower, which by stage 7 forms a slotted tube that will develop into the gynoecium (Fig. 2l) (Smyth et al., 1990). In a stage 6 p35S-PI p35S-AP3 flower, cells in the center of the floral meristem have already initiated small bulges (usually three or four) that will develop into another whorl of stamens (Fig. 2J). Additional whorls of stamens may form interior to these fourth whorl stamens at a later time in the development of the flower (Fig. 2K).

Vegetative phenotypes resulting from ectopic expression of PI and AP3

Ectopic expression of both class B genes causes vegetative phenotypes that are not present in p35S-AP3 or p35S-PI, p35S-
PI p35S-AP3 plants are spindly and early flowering, and the leaves of these plants (both rosette and cauline) are smaller and curled around the midrib (Fig. 1, compare D with E). This curled leaf phenotype is similar to that observed in plants that ectopically express AG (p35S-AG) (Mizukami and Ma, 1992) and in mutations in curly leaf (clf), which result in ectopic expression of AG in both leaves and flowers (Coupland et al., 1993; J. Goodrich, G. Coupland, and E.M.M., unpublished data). This leaf curling appears to be at least somewhat environmentally controlled since reduced leaf curling is observed at lower temperatures (16°C) and in short days (8 hours of light) (data not shown).

An additional leaf phenotype caused by p35S-PI p35S-AP3 is the partial transformation of some of the cauline leaves to petals. The petaloid cauline leaves are smaller and thinner than normal cauline leaves, and often have a white fringe of tissue along the curled edges of the leaf (Fig. 1, compare F with G). The morphology of cells on the abaxial surface of these organs are leaf-like (Fig. 2M) except for the cells along the leaf edges which are small and round in appearance with the cuticular thickenings characteristic of the abaxial surface of a petal blade (Fig. 2N,O). The adaxial surface of these organs consists of small roundish cells which do not resemble the puzzle-shaped cells of cauline leaves and are somewhat similar to cells on the adaxial surface of a petal blade, although they are not ridged and the cuticular thickenings are less pronounced (Fig. 2P).

**AP3 RNA and protein and PI RNA are detected throughout p35S-PI p35S-AP3 plants**

To confirm that both AP3 and PI are constitutively expressed throughout p35S-PI p35S-AP3 plants, in situ hybridization and immunolocalization studies were performed. AP3 RNA (Fig. 3, compare A with B) and PI RNA (Fig. 3, compare C with D) were detected throughout the flower and inflorescence stem of p35S-PI p35S-AP3. Immunolocalization using an AP3-specific antibody shows that AP3 protein (Fig. 3, compare E,F with G,H) is distributed throughout the flowers and stem of p35S-PI p35S-AP3 plants, analogous to the distribution of AP3 RNA. This correlation between the AP3 RNA and protein distributions in p35S-PI p35S-AP3 is in contrast to that found in p35S-AP3 (Jack et al., 1994). Although AP3 RNA was detected throughout the inflorescence and vegetative tissues of p35S-AP3, AP3 protein was only detected at high levels in the second, third, and fourth whorls of the flowers, suggesting that AP3 was posttranscriptionally regulated in p35S-AP3 (Jack et al., 1994). A similar posttranscriptional regulation of AP3 was observed in the second whorl of a pi-1 mutant, suggesting that PI was involved not only in the transcriptional regulation of AP3 but also posttranscriptionally (Jack et al., 1994). Here we show that upon addition of ectopic PI expression (in p35S-PI p35S-AP3), AP3 protein is now detectable in all places where AP3 RNA is expressed, including the cauline leaves, the inflorescence stem, and in all regions of the flowers. This result provides evidence that PI is sufficient for the posttranscriptional control of AP3, perhaps by stabilizing AP3 protein in an AP3/PI heterodimer, since AP3 and PI are known to interact in solution (Goto and Meyerowitz, 1994).

**Phenotypes of p35S-PI p35S-AP3 in floral mutants**

**Class A mutants**

*ap1-1*

Flowers of *ap1-1* exhibit both inflorescence and floral defects.
Fig. 2. Development of wild-type (A-D,I) and p35S-PI p35S-AP3 (E-H, J-P) plants viewed by scanning electron microscopy. Flowers staged according to Smyth et al. (1990). Size bars represent 100 μm for (A,B,E,F,N) and 10 μm for (C,D,G-M,O,P). Numbers indicate the whorl.
(A) Mature wild-type flower. (B) Wild-type sepal. (C) High magnification of sepal showing the characteristic epidermal morphology. (D) Stage 8 wild-type flower. (E) Mature p35S-PI p35S-AP3 flower. (F) p35S-PI p35S-AP3 first whorl petal. (G) High magnification of p35S-PI p35S-AP3 petal showing characteristic petal epidermal morphology. (H) Side view of a first whorl organ of p35S-PI p35S-AP3 stage 8 flower. The first whorl organs of p35S-PI p35S-AP3 do not have the characteristic elongate sepal cells found in wild type as shown in D. (I) Wild-type stage 7 flower. A slotted cylinder has formed in the center of the floral meristem which will develop into the gynoecium. (J) A stage 6 p35S-PI p35S-AP3 flower. Three bulges are visible in the center of the flower which will give rise to fourth whorl stamens. (K) Top down view of p35S-PI p35S-AP3. Three whorls of stamens are visible consisting of 6 St, 4 St, and 2 St. The 2 fifth whorl stamens are indicated with a white arrow. (L) Carpelloid structures (indicated by white arrow) which are rarely found in p35S-PI p35S-AP3 flowers. (M) Leaf-like abaxial surface of a petaloid cauline leaf. (N) Curls margins of a petaloid cauline leaf showing small round cells on the edge of the organ (indicated by black arrow). (O) High magnification of these small round cells showing a similar cellular morphology as the abaxial surface of a petal blade. (P) Adaxial surface of petaloid cauline leaf. The cells are not leaf-like and somewhat resemble petal cells.
These include a transformation of the first whorl sepals to leaf-like organs, the almost complete absence of second whorl petals, and the presence of secondary flowers that arise in the axils of the first whorl leaf-like organs (Irish and Sussex, 1990; Bowman et al., 1993). Flowers of p35S-PI p35S-AP3 ap1-1 (Figs 4A, 5E) consist of petaloid leaf-like organs in the first whorl with an epidermal morphology intermediate between that of leaves and petals (Fig. 5, compare A with F). The first whorl organs of later-arising flowers are petals with few leaf-like characteristics. Second whorl organ primordia are often initiated (Fig. 5, compare B with G,H) and these primordia develop into petals, stamen/petal mosaic organs, and stamens. Stamens are found in the third and fourth whorls. The number of organs in each whorl is variable. Axillary stipules at their base (Fig. 5K). Stamens develop in the second whorl organ primordia (Irish and Sussex, 1990; Bowman et al., 1993). Ectopic expression of both AP3 and PI is responsible for the formation of flowers consisting almost entirely of stamens, with some petal/stamen organs (Figs 4B, 5I). The first whorl medial organs of later-arising flowers are petals with an epidermal morphology intermediate between that of leaves and petals (Fig. 5, compare A with F). The first whorl lateral organs have an epidermal morphology identical to that of leaves (Fig. 5, compare A with F). Most flowers of p35S-PI p35S-AP3 ap1-1 flowers are 3.3 (flowers 1-5), 1.4 (flowers 6-10), and 1.2 (flowers 11-15).

**ap2-2**

Strong ap2 mutants have medial first whorl carpels, lateral first whorl organs that are missing or leaf-like, no second whorl organs, a reduction in the number of third whorl stamens, and carpels which are sometimes abnormal in the fourth whorl (Bowman et al., 1989, 1991; Kunst et al., 1989). Ectopic expression of both PI and AP3 in an ap2-2 background results in flowers consisting almost entirely of stamens, with some petal/stamen organs (Figs 4B, 5I). The first whorl medial organs are stamens while the first whorl lateral organs have an epidermal morphology intermediate between petals and stamens (Fig. 5, compare C with J). These lateral organs are sometimes leaf-like with stellate trichomes on their surface and stipules at their base (Fig. 5K). Stamens develop in the second (Fig. 5L), third, fourth and any interior whorls. Ectopic B function in an ap2-2 background results in the initiation and development of second whorl organs and in an increased number of third whorl organs as compared to ap2-2.

**Class B mutants**

**pi-1**

pi-1 flowers consist of two outer whorls of sepals and an abnormally large gynoecium in the center of the flower (Fig. 5M; Bowman et al., 1989; Hill and Lord, 1989). Ectopic expression of PI and AP3 does not fully rescue pi-1. p35S-PI p35S-AP3 pi-1 flowers consist of two outer whorls of petals, a third whorl which contains stamens, carpelloid stamens, filaments, or the absence of organs, and a fourth whorl staminal/carpelloid structure (Figs 4C, 5N,O). Organs from the third and fourth whorls are often fused (Fig. 5N). p35S-PI p35S-AP3 plants heterozygous for pi-1 exhibit a similar but less pronounced phenotype (Fig. 4D). The outer three whorls of these flowers, consist of four petals, four petals, and six stamens. The fourth whorl organ has features of both stamens and carpels. SEM analyses of these fourth whorl structures show that they arise in a carpel-like fashion as a slotted tube (Fig. 5P). A wild-type gynoecium consists of two carpels whose place of fusion is marked by a false septum characterized by vertical files of cells. The carpels are tipped by a short style and stigmatic papillae (Fig. 5Q). The fourth whorl structures of p35S-PI p35S-AP3 pi-1+ and p35S-PI p35S-AP3 pi-1/+ are different in overall appearance from wild-type carpels; the fused carpelloid structures (usually two but sometimes three or four) are wider at the top and become narrower near their base (Fig. 5, compare Q with S). Files of cells along the length of their fusion sites resemble those of a wild-type septum, and stigmatic papillae are present on the top of the organ much as in a wild-type gynoecium, but no style is present. Ovules are present inside the carpelloid structures, but the plants do not produce seed. The epidermal cellular morphology of the fourth whorl organs is quite different from that characteristic of ovaries; no epicuticular wax is evident (Fig. 5, compare R with T) and the shape of the cells is reminiscent of epidermal anther cells. Cells at the narrow base of these fourth whorl structures are arranged in files like those of a stamen filament. As these organs senesce, the upper “ovary-like” part turns yellow (similar to an anther) but the filament-like basal part does not. Thus, these organs have both carpel features (stigmatic papillae, ovules) and stamen features (epidermal morphology, color).

**pi-2**

Flowers of the intermediate pi-2 allele have sepals in the second whorl and carpelloid organs, filaments, or an absence of organs in the third whorl (Bowman et al., 1991). Ectopic expression of both PI and AP3 fully rescues a pi-2 mutant with the flowers of p35S-PI p35S-AP3 pi-2 indistinguishable from those of p35S-PI p35S-AP3.

**pi-3**

Flowers of the weaker pi-3 allele contain four sepals in the second whorl and carpels, staminoid carpels, or filaments in the third whorl (Bowman et al., 1991). Flowers of p35S-PI p35S-AP3 pi-3 have a phenotype similar to that described above for p35S-PI p35S-AP3 pi-1 flowers. There is often a fourth whorl staminal/carpelloid structure with the same morphology as seen in p35S-PI p35S-AP3 pi-1/+ flowers. The third whorl is often wild type with six stamens, however, the stamens are occasionally missing or replaced by filaments. pi-3 also becomes partially dominant in p35S-PI p35S-AP3 plants. The fourth whorl of p35S-PI p35S-AP3 pi-3/+ flowers sometimes contain the novel staminoid/carpelloid structure or stamens with carpelloid characteristics.

**ap3-3**

Flowers mutant for ap3-3 have two outer whorls of sepals and two inner whorls of carpels (Jack et al., 1992). Ectopic expression of both PI and AP3 fully rescues an ap3-3 mutant. The flowers of p35S-PI p35S-AP3 ap3-3 are indistinguishable from those of p35S-PI p35S-AP3.

**ap3-1**

Flowers containing the ap3-1 temperature sensitive mutation have sepals in the second whorl; stamens, carpelloid stamens, or carpelloid organs in the third whorl, when grown at 25°C (Bowman et al., 1989). Ectopic expression of both B class genes rescues the second and third whorl defects of the weak ap3-1 allele.
Class C mutants

**ag-3**

Mutations in *ag* result in the formation of indeterminate flowers which produce sepals, petals and petals in a repeating pattern (Bowman et al., 1991). Ectopic expression of *PI* and *AP3* in an *ag-3* background results in indeterminate flowers consisting entirely of petals (Fig. 4E).

**superman (sup-1)**

Mutations at the *superman* (*sup-1*) locus result in the production of extra stamens and a reduction in carpel tissue (Schultz et al., 1991; Bowman et al., 1992). One explanation of this phenotype is that *SUP* increases cell division in the third whorl, while repressing it in the fourth (Sakai et al., 1995). p35S-PI p35S-AP3 *sup-1* flowers consist of two outer whorls of petals and an indeterminate number of stamens (Fig. 4F). A central dome of cells continues to proliferate and produce stamens until the flower senesces (Fig. 6J). This central dome of undifferentiated cells is visible after the fourth whorl stamen primordia have initiated (Fig. 6K). p35S-PI p35S-AP3 *sup-1* flowers average more than 18 stamens (although this number is somewhat difficult to determine accurately, since the meristem continues to produce stamens even as the flowers are dying), which is greater than the number found in *sup-1* flowers (14.6) (Bowman et al., 1992) or p35S-PI p35S-AP3 flowers (15.6). The enhancement of the *sup-1* phenotype by p35S-PI p35S-AP3 is greater than that exhibited by p35S-AP3, since p35S-PI p35S-AP3 *sup-1* flowers are completely indeterminate while p35S-AP3 *sup-1* flowers have extra whorls but do not proliferate indefinitely (Jack et al., 1994). An additional observation in p35S-PI p35S-AP3 *sup-1* flowers is the delayed initiation of the fourth whorl primordia as compared to the development of the fourth whorl in p35S-PI p35S-AP3 or *sup-1* flowers (compare Fig. 6L with Fig. 2J).

Ectopic expression of both *PI* and *AP3* rescues the floral organ identity defects of *lfy* and *ufo*

Ectopic expression of both class B genes rescues the floral organ identity defects of *lfy* and *ufo*. *LFY* and *UFO* are involved in positive regulation of the B function in flowers, as demonstrated by the reduction or elimination of petals and stamens in *lfy* and *ufo* mutants and a corresponding decrease in the expression of *PI* and *AP3* (Huala and Sussex, 1992; Weigel et al., 1992; Weigel and Meyerowitz, 1993; Levin and Meyerowitz, 1995). Strong *lfy* alleles (such as *lfy-6*) have flowers consisting of sepals, carpels, and sepal/carpel mosaic organs. Strong *ufo* alleles (such as *ufo-2*) show a reduction in the number of petals and stamens; in general these organs are replaced by sepals, filaments, carpels and mosaic organs. Flowers of p35S-PI p35S-AP3 *lfy-6* consist of sepal-like organs, petals, stamens and mosaic organs consisting of various combinations of sepal, petal and stamen tissue (Figs 4I, 6A,B). The outer whorls usually consist of sepals,
sepal/petal mosaic organs and petals. Interior to these organs are petal/stamen mosaic organs and stamens. The flowers of p35S-PI p35S-AP3 ufo-2 have petaloid organs in the outer two whorls and stamens in the inner whorls with the occasional appearance of filaments (Figs 4G, 6E). The rescue of the organ identity defects of lfy and ufo by ectopic expression of both B class genes is much greater than that resulting from ectopic expression of either PI or AP3 alone (Jack et al., 1994; Krizek and Meyerowitz, unpublished data).

LFY and UFO are also involved in the promotion of floral meristem identity, and mutations in these genes cause various inflorescence defects. One example is the presence of subtending leaf-like bracts on flowers (Weigel et al., 1992; Levin and Meyerowitz, 1995). Similar leaf-like organs are found below p35S-PI p35S-AP3 lfy-6 and p35S-PI p35S-AP3 ufo-2 flowers, except that they now have petal characteristics. These organs are narrower than those found in lfy-6 or ufo-2, tapering at their base, and are pale green or white in color (Fig. 4H). The surface of these organs is quite petal-like; the cells are small and round with petal cuticular morphology (Fig. 6H).

The observation that these leaf-like bracts can be converted to petaloid organs is consistent with the presence of LFY RNA in these organs, which apparently indicates that they are floral (Weigel et al., 1992).

The spiral pattern of floral organ initiation found in lfy-6 flowers is also present in some p35S-PI p35S-AP3 lfy-6 flowers (Fig. 6C). The severity of this defect seems to vary, perhaps with position of the flower on the inflorescence; some flowers exhibit a nearly whorled pattern of organ primordia (Fig. 6D). Defects found in ufo that are still present when PI and AP3 are ectopically expressed are the disproportionately faster growth rate of the second whorl organs (Fig. 6F) and the presence of filaments on the inflorescence stem and squamule-like filaments at the base of the bracts (Fig. 6G). Thus, ectopic expression of PI and AP3 is unable to rescue inflorescence defects such as bract formation or defects in floral organ positioning and growth of lfy and ufo.

**AP3 and PI are sufficient to autoregulate in floral tissue**

Much evidence has accumulated that AP3 and PI work together in an autoregulatory loop to maintain each other’s expression (Goto and Meyerowitz, 1994; Jack et al., 1994). Experiments with an AP3 promoter-reporter gene (β-glucuronidase) construct showed that AP3 and PI appear to be sufficient for activation of the AP3 promoter in flowers (Jack et al., 1994). In a wild-type background this construct directs GUS staining in the petals, stamens and at the base of the first whorl sepalas (Fig. 7A,C), a pattern similar to that seen for AP3 RNA. Staining of p35S-AP3 pAP3-GUS flowers showed GUS expression in the second, third and fourth whorls, consistent with the distribution of AP3 protein, and thus indicates that AP3 is able to regulate its own transcription in regions where PI is active (Jack et al., 1994). In p35S-PI pAP3-GUS flowers, GUS activity is detected in the first whorl (Krizek and Meyerowitz, unpublished data), providing additional evidence that PI is involved in the autoregulation of AP3.

p35S-PI p35S-AP3 plants containing the pAP3-GUS construct showed GUS activity in all four whorls of the flower and parts of the pedicel, but not in the inflorescence stem or cauline leaves (Fig. 7B,D). Since p35S-PI p35S-AP3 plants show a vegetative phenotype, and neither p35S-PI nor p35S-AP3 show one, we would expect that both AP3 and PI proteins are present in these vegetative tissues, and this has been confirmed for AP3 protein (Fig. 3G,H). However, AP3 and PI are not able to activate the pAP3-GUS gene here, indicating that they are not sufficient for their autoregulation in nonfloral tissue. PI and AP3 may require an additional flower-specific
Fig. 5. SEM characterization of floral homeotic mutants containing p35S-PI p35S-AP3. Scanning electron micrographs of ap1-1 (A,B), ap2-2 (CD), pi-1 (M), wild-type (Q,R), and p35S-PI p35S-AP3 flowers mutant for ap1-1 (E-H), ap2-2 (I-L), pi-1 (N-P), and pi-1/+ (S,T). Bars represent 100 μm for (E,I,N,Q,S), and 10 μm for (A-D,F,H,J-M,P,R,T). AM, axillary meristem. The numbers indicate whorls. (A) Surface morphology of a first whorl organ of ap1-1. (B) ap1-1 flower showing the absence of second whorl organs. (C) Surface morphology of a first whorl organ of ap2-2. (D) ap2-2 flower showing the absence of second and third whorl organs. (E) p35S-PI p35S-AP3 ap1-1 flower. The outer whorl contains leaf-like petals, indicated by black arrows. (F) Surface morphology of a first whorl leaf-like petal. (G) Stage 6 p35S-PI p35S-AP3 ap1-1 flower. A black arrow points to a probable second whorl primordia. Since this is a later flower, it is unlikely that this outgrowth of cells is the floral meristem of an axillary flower. (H) Stage 9 p35S-PI p35S-AP3 ap1-1 flower showing a second whorl organ (white arrow). (I) p35S-PI p35S-AP3 ap2-2 flower. These flowers consist entirely of stamens except for the lateral first whorl organs which develop into petaloid stamens, indicated by white arrows. (J) Surface of a first whorl petaloid stamen. (K) The first whorl petaloid stamens sometimes have leaf-like qualities such as stipules (indicated by arrows). (L) A stage 7 p35S-PI p35S-AP3 ap2-2 flower showing that second whorl primordia are sometimes initiated (indicated by arrows). (M) pi-1 flower. (N) p35S-PI p35S-AP3 pi-1 flower. Stamens or carpelloid organs are visible in the third whorl. One of these carpelloid stamens (marked with arrow) is fused to the fourth whorl carpelloid/staminoid structure. (O) p35S-PI p35S-AP3 pi-1 flower showing the absence of stamens in the third whorl. One filament is present and the large fourth whorl carpelloid/staminoid structure (indicated by black arrow) is probably due to incorporation of third whorl cells. (P) A stage 6 p35S-PI p35S-AP3 pi-1 flower. The fourth whorl organ appears to develop as in wild type with the invasion of cells in the center of the meristem. (Q) Wild-type mature gynoecium consisting of two fused carpels. The carpels are topped by a short style and stigmatic tissue. (R) Surface morphology of wild-type ovary epidermal cells. (S) p35S-PI p35S-AP3 pi-1/+ flower. A carpelloid/staminoid structure has formed in the fourth whorl. (T) Surface morphology of this fourth whorl carpelloid/staminoid structure.

factor to autoregulate or alternatively, there could be a vegetative factor that represses the ability of AP3 and PI to autoregulate.

DISCUSSION

**PI and AP3 are sufficient in flowers to specify petals and stamens in combination with class A and C genes**

Ectopic expression of both class B genes gives rise to flowers with petals in whorls one and two and stamens in the interior whorls. This result demonstrates that AP3 and PI are sufficient to provide the B organ identity function in flowers (Fig. 8). Flowers of p35S-PI p35S-AP3 ap2-2 plants consist entirely of stamens and staminoid organs as predicted by the ABC model when B and C functions are active in all four whorls. Similarly, flowers of p35S-PI p35S-AP3 ag-3 plants consist entirely of petals as predicted when A and B functions are active throughout the flower. Thus, the results of ectopic expression of the B function genes provide new experimental evidence in support of the hypotheses of the ABC model. These are that: the identity of an organ is dependent upon the combination of organ identity genes expressed by the cells giving rise to that organ and that the effects of the organ identity genes are not restricted to a particular region of the flower. This last premise predicts that any type of organ can occur in any whorl of a flower, and this has now been demonstrated. For example, all four types of organs can be found in whorl one: sepals (wild type), petals (p35S-PI p35S-AP3), stamens (p35S-PI p35S-AP3 ap2-2), and carpels (ap2-2).

**Ectopic PI and AP3 expression causes partial transformation of later developing leaves to petals**

Ectopic expression of the B class genes results in the partial transformation of some of the later-produced cauline leaves into petaloid leaves. The presence of stigmatic papillae on some cauline leaves of p35S-AG plants shows that C function genes can also act in cauline leaves (Mizukami and Ma, 1992). It is not reported, however, if this phenotype is only observed in more apical cauline leaves. Our results suggest that there is a gradient of floral character during the life of the plant that could arise either by increasing amounts of floral activators or by decreasing amounts of repressors of flowering. This is supported by the acropetally decreasing severity of the floral meristem identity defects of ify-6 and ap1-1 (Irish and Sussex, 1990; Weigel et al., 1992). The presence of a gradient of floral quality has also been previously suggested by work on tobacco (McDaniel and Hartnett, 1993). In these studies, explants of axillary buds were attached to stem cuttings, and the number of nodes produced by the bud before flowering were counted. Buds attached to more apical stem cuttings produced fewer nodes before flowering than buds of an equivalent position attached to a more basal stem cutting.

Our results would seem to indicate that ectopic expression of the organ identity genes is not sufficient to change the developmental fate of a leaf to that of a floral organ unless these organs possess a sufficient degree of floral character. This can seemingly be acquired by primordia in at least two ways: being specified as floral or alternatively, being produced late in the development of an inflorescence. The first case is exemplified by the floral leaves or bracts of ify and ufo mutants which become petaloid in the presence of ectopic B function and by the carpelloid bracts produced in tobacco plants overexpressing the tobacco AG homolog (p35S-NAG) (Mandel et al., 1992a). The second case describes the later cauline leaves of p35S-PI p35S-AP3 plants, which are partially transformed to petals. This floral character does not appear to be specified by either LFY or AP1 alone, since petaloid bracts are found in p35S-PI p35S-AP3 ify null mutants, and petaloid cauline leaves are found in p35S-PI p35S-AP3 ap1 mutants. Furthermore, it seems unlikely that this floral character is specified by LFY and AP1 together since AP1 is not expressed in the bracts of ify-6 (D. Weigel, personal communication), which become petaloid when B function is ectopically expressed. Therefore, it appears that the factors responsible for the partial petaloid transformations of bracts and cauline leaves are as yet unidentified.

**The earlier expression of AP3 and PI in floral primordia does not affect the time course of organ development**

For all of the homeotic mutants except AG, floral organs develop on a schedule corresponding to their whorl identity and not their organ identity (Bowman et al., 1989). The earliest
primordia to differentiate from the floral meristem are the first whorl organs, independent of the type of organ that will differentiate in this region. The second and third whorl primordia arise about the same time in development, with the second whorl primordia alternate in position with the first whorl primordia. Last to differentiate are cells in the center of the meristem which form the fourth whorl organs. The results of ectopic expression of AP3 and PI provide further evidence that the identity of an organ and the temporal development of that organ are distinct processes. The second whorl petals of p35S-PI p35S-AP3 arise developmentally later than the first whorl petals even though all cells in the first and second whorls express the A and B class genes from their inception. Similarly, the fourth whorl stamens arise later than those in the third whorl. Thus, the earlier expression of the B class genes in a floral meristem does not alter the relative temporal development of the floral organs produced by that meristem. These experiments also demonstrate that the organ identity and the whorl or positional identity of floral organ primordia are distinct.

**p35S-PI p35S-AP3 Makes pi-1 and pi-3 partially dominant**

A surprising result from these studies is that ectopic PI and AP3 expression does not rescue pi-1 or pi-3 and makes these
recessive alleles partially dominant. Ectopic B function does rescue the pi-2 mutant. One explanation for the dominant phenotypes of these flowers is that pi-1 and pi-3 may be acting in a dominant negative manner. The pi-1 mutation results in a stop codon 22 amino acids after the MADS domain. The mutation in pi-3 is a substitution of Ala49 by Ser in the MADS domain of the protein. It is possible that these genes could encode proteins of sufficient length to interact with both the endogenous and transgenic AP3 protein. The AP3/PI(pi-1, pi-3) protein complexes might be inactive due to an inability to bind DNA or perform some other function. It is possible that quite high levels of the mutant gene products could be produced since PI and AP3 overproduction from the transgenes would be expected to activate the endogenous pi gene.

An alternative explanation is that the development of stamens is sensitive to the levels of PI protein. A mutation in one copy of PI (p35S-PI p35S-AP3 pi-1/+ ) would result in decreased levels of active PI protein relative to p35S-PI p35S-AP3 in a wild-type background. If the production of stamens, particularly in the fourth whorl, is sensitive to the level of AP3/PI complex, this decrease in the amount of PI could result in the observed phenotype.

Role of AP3 and PI in cellular proliferation in the floral meristem

That AP3 and PI play a role in the determinacy of the floral meristem is indicated by the presence of additional whorls of stamens in p35S-PI p35S-AP3 flowers. The rescue of second whorl primordia in class A mutants by ectopic expression of PI and AP3 also indicates a role for the B class genes in proliferation. This second whorl defect of ap1 and ap2 mutants is believed to result from AG, since second whorl primordia are present in ap1-1 ag-2 and ap2-2 ag-2 double mutant flowers (Bowman et al., 1991). The expression of PI and AP3 is reduced in ap2 mutants (Jack et al., 1992; Goto and Meyerowitz, 1994), and the elimination of the second whorl organs may be due in part to the reduced activity of the B function and in part by ectopic AG. The B and C class genes work in opposition in the growth of the floral meristem: AP3/PI act to promote cell division while AG acts to suppress cell division. The decreased number of third whorl organs in pi and ap3 mutants are consistent with this role (Bowman et al., 1989; Jack et al., 1992). A similar function has been proposed for DEFA and GLO, the Antirrhinum homologs of AP3 and PI, (Tröbner et al., 1992) based on the observation that mutations...
in DEF and GLO (unlike those in AP3 and PI) result in an absence of fourth whorl organs.

The results from these ectopic expression experiments have demonstrated not only that the class B genes AP3 and PI are sufficient to direct the floral development of petals and stamens with the class A and C genes respectively, but have also provided evidence that these genes play an additional role in cellular proliferation in the floral meristem. Furthermore, these experiments suggest that there are additional unknown factors that signal cells that they are floral, thereby allowing both the organ identity and autoregulatory activities of the B function genes. Identification of these factors and their function should provide an important clue to the molecular mechanism of floral induction.

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REFERENCES

Bowman, J. L., Smyth, D. R., and Meyerowitz, E. M. (1989). Genes directing flower development in Arabidopsis. Plant Cell 1, 37-52.

Bowman, J. L., Smyth, D. R., and Meyerowitz, E. M. (1991). Genetic interactions among floral homeotic genes of Arabidopsis. Development 112, 1-20.

Bowman, J. L., Sakai, H., Jack, T., Weigel, D., Mayer, U., and Meyerowitz, E. M. (1992). SUPERMAN, a regulator of floral homeotic genes in Arabidopsis. Development 114, 599-615.

Bowman, J. L., Alvarez, J., Weigel, D., Meyerowitz, E. M., and Smyth, D. R. (1993). Control of flower development in Arabidopsis thaliana by APETALA1 and interacting genes. Development 119, 721-743.

Bowman, J. L. (1994). Flowers: Floral Organs and Floral Organ Identity Mutants. In Arabidopsis: An Atlas of Morphology and Development (ed. J. Bowman), pp. 162-163, 244, New York: Springer-Verlag.

Coen, E. S., and Meyerowitz, E. M. (1991). The war of the whorls: genetic interactions controlling flower development. Nature 353, 31-37.

Coupland, G., Dash, S., Goodrich, J., Lee, K., Long, D., Martin, M., Puangngoonlee, P., Puterill, J., Robson, F., Sundberg, E., and Wilson, K. (1995). Molecular and genetic analysis of the control of flowering time in response to daylength in Arabidopsis thaliana. Flowering Newsletter 16, 27-32.

Drews, G. N., Bowman, J. L., and Meyerowitz, E. M. (1991). Negative regulation of the Arabidopsis homeotic gene AGAMOUS by the APETALA2 product. Cell 66, 991-1002.

Goto, K., and Meyerowitz, E. M. (1994). Function and regulation of the Arabidopsis floral homeotic gene PISTILLATA. Genes Dev. 8, 1548-1560.

Halfter, U., Ali, N., Stockhaus, J., Ren, L., and Chua, N.-H. (1994). Ectopic expression of a single homeotic gene, the Petunia gene green petal, is sufficient to convert sepals to petaloid organs. EMBO J. 13, 1443-1449.

Hill, J. P., and Lord, E. M. (1989). Floral development in Arabidopsis thaliana: a comparison of the wild-type and the homeotic pistillata mutant. Can. J. Bot. 67, 2922-2936.

Huala, E., and Sussex, I. M. (1992). LEAFY interacts with floral homeotic genes to regulate Arabidopsis floral development. Plant Cell 4, 901-913.

Irish, V. F., and Sussex, I. M. (1990). Function of the apetala1 gene during Arabidopsis floral development. Plant Cell 2, 741-753.

Jack, T., Brockman, L. L., and Meyerowitz, E. M. (1992). The homeotic gene APETALA3 of Arabidopsis thaliana encodes a MADS box and is expressed in petals and stamens. Cell 68, 683-687.

Jack, T., Fox, G. L., and Meyerowitz, E. M. (1994). Arabidopsis homeotic gene APETALA3 ectopic expression: transcriptional and posttranscriptional regulation determine floral organ identity. Cell 76, 703-716.

Jefferson, R. A., Kavanagh, T. A., and Bevan, M. W. (1987). GUS fusions: β-glucuronidase as a sensitive and versatile gene fusion marker in higher plants. EMBO J. 6, 3901-3907.

Jofuku, K. D., den Boer, B. G. W., Van Montagu, M., and Okamura, J. K. (1994). Control of Arabidopsis flower and seed development by the homeotic gene APETALA2. Plant Cell 6, 1211-1225.

Klimyuk, V. I., Carroll, B. J., Thomas, C. M., and Jones, J. M. (1993). Alkali treatment for rapid preparation of plant material for reliable PCR analysis. Plant J. 3, 493-494.

Kunst, L., Klenz, J. E., Martinez-Zapater, J., and Haughn, G. W. (1989) AP2 gene determines the identity of perianth organs in flowers of Arabidopsis thaliana. Plant Cell 1, 1195-1208.

Levin, J. Z., and Meyerowitz, E. M. (1995). UFO: an Arabidopsis gene involved in both floral meristem and floral organ development. Plant Cell 7, 529-548.

Mandel, M. A., Bowman, J. L., Kempin, S. A., Ma, H., Meyerowitz, E. M., and Yanofsky, M. F. (1992a). Manipulation of flower structure in transgenic tobacco. Cell 71, 133-143.

Mandel, M. A., Gustafson-Brown, C., Savidge, B., and Yanofsky, M. F. (1992b). Molecular characterization of the Arabidopsis floral homeotic gene APETALA1. Nature 360, 273-277.

McBride, K. E., and Summerfelt, K. R. (1990). Improved binary vectors for Agrobacterium-mediated plant transformation. Plant Mol. Biol. 14, 269-276.

McDaniel, C. N. and Hartnett, L. K. (1993). Floral-stimulus activity in tobacco stem pieces. Plant 99, 579-583.

Meyerowitz, E. M., Bowman, J. L., Brockman, L. L., Drews, G. N., Jack, T. J., Sieburth, L., and Weigel, D. (1991). A genetic and molecular model for flower development in Arabidopsis thaliana. Development Supplement 1, 157-167.

Mizukami, Y., and Ma, H. (1992). Ectopic expression of the floral homeotic gene AGAMOUS in transgenic Arabidopsis plants alters floral organ identity. Cell 71, 119-131.

Sakai, H., Medrano, L., and Meyerowitz, E. M. (1995). Role of SUPERMAN in maintaining Arabidopsis floral whorl boundaries. Nature (in press).

Schultz, E. A., Pickett, F. B., and Haughn, G. W. (1991). The FLO10 gene product regulates the expression domain of homeotic genes AP3 and PI in Arabidopsis flowers. Plant Cell 3, 1221-1237.

Smyth, D. R., Bowman, J. L., and Meyerowitz, E. M. (1990). Early flower development in Arabidopsis. Plant Cell 2, 755-767.

Tröbner, W., Ramirez, L., Motte, P., Hue, I., Huijser, P., Lönnig, W., Saedler H., Sommer, H., and Schwarz-Sommer, Z. (1992). GLOBOSA: a homeotic gene which interacts with DEFICIENS in the control of Antirrhinum floral organogenesis. EMBO J. 11, 4693-4704.

Weigel, D., Alvarez, J., Smyth, D. R., Yanofsky, M. F., and Meyerowitz, E. M. (1992). LEAFY controls floral meristem identity in Arabidopsis. Cell 69, 843-859.

Weigel, D., and Meyerowitz, E. M. (1993). Activation of floral homeotic genes in Arabidopsis. Science 261, 1723-1726.

Weigel, D., and Meyerowitz, E. M. (1994). The ABCs of floral homeotic genes. Cell 78, 203-209.

Weigel, D. (1995). The APETALA2 domain is related to a novel type of DNA binding domain. Plant Cell 7, 388-389.

Yanofsky, M. F., and Ma, H., Bowman, J. L., Drews, G. N., Feldmann, K. A., and Meyerowitz, E. M. (1990). The protein encoded by the Arabidopsis homeotic gene agamous resembles transcription factors. Nature 346, 35-39.

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