SUPERWOMAN1 and DROOPING LEAF genes control floral organ identity in rice

Nobuhiro Nagasawa1,4, Masahiro Miyoshi1,*, Yoshio Sano2, Hikaru Satoh3, Hiroyuki Hirano1, Hajime Sakai4,† and Yasuo Nagato1,†

1Graduate School of Agricultural and Life Sciences, University of Tokyo, Tokyo 113-8657, Japan
2Faculty of Agriculture, Hokkaido University, Sapporo 060-8589, Japan
3Faculty of Agriculture, Kyushu University, Fukuoka 812-8581, Japan
4DuPont Company, Agriculture and Nutrition, Delaware Technology Park 200, 1 Innovation Way, Newark, DE 19714, USA
*Present address: Orynova Co. Ltd., Iwata 438-0802, Japan
†Authors for correspondence (e-mail: anagato@mail.ecc.u-tokyo.ac.jp and Hajime.Sakai@usa.dupont.com)

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SUMMARY

We analyzed recessive mutants of two homeotic genes in rice, SUPERWOMAN1 (SPW1) and DROOPING LEAF (DL). The homeotic mutation spw1 transforms stamens and lodicules into carpels and palea-like organs, respectively. Two spw1 alleles, spw1-1 and spw1-2, show the same floral phenotype and did not affect vegetative development. We show that SPW1 is a rice APETALA3 homolog, OsMADS16. In contrast, two strong alleles of the dl locus, drooping leaf-superman1 (dl-sup1) and drooping leaf-superman2 (dl-sup2), cause the complete transformation of the gynoecium into stamens. In these strong mutants, many ectopic stamens are formed in the region where the gynoecium is produced in the wild-type flower and they are arranged in a non-whorled, alternate pattern. The intermediate allele dl-1 (T65), results in an increase in the number of stamens and stigmas, and carpels occasionally show staminoid characteristics. In the weakest mutant, dl-2, most of the flowers are normal. All four dl alleles cause midrib-less drooping leaves. The flower of the double mutant, spw1 dl-sup, produces incompletely differentiated organs indefinitely after palea-like organs are produced in the position where lodicules are formed in the wild-type flower. These incompletely differentiated organs are neither stamens nor carpels, but have partial floral identity. Based on genetic and molecular results, we postulate a model of stamen and carpel specification in rice, with DL as a novel gene controlling carpel identity and acting mutually and antagonistically to the class B gene, SPW1.

Key words: Rice, Oryza sativa, DROOPING LEAF, SUPERWOMAN1, Floral mutants, Floral organ identity, Homeotic mutations, MADS box

INTRODUCTION

Genetic and molecular mechanisms of flower development have been intensively studied in two dicot species, Arabidopsis thaliana and Antirrhinum majus. In these species, rapid progress has been made toward the understanding of the genetic regulation of floral organ specification. Genetic analyses of homeotic mutants in two model plants led to a genetic model of flower development (Carpenter and Coen, 1990; Schwarz-Sommer et al., 1990; Bowman et al., 1991). Several genetic analyses indicated that the genetic mechanisms specifying floral organ identities are conserved between the two distantly related dicot plants Arabidopsis and Antirrhinum (for a review, see Coen and Meyerowitz, 1991). Further genetic and molecular analyses indicated that the genetic mechanisms specifying floral organ identities are conserved between the two distantly related dicot plants Arabidopsis and Antirrhinum. One of them, superman (sup) is characterized as a mutant that produces extra-stamens at the expense of carpels (Schultz et al., 1991; Bowman et al., 1992). Although SUP function was once thought to be the negative regulator of B function genes in whorl 4, SUP expression pattern in the wild type and 35S-AP3 flower
suggests that the function of SUP is rather to regulate cell proliferation in whorls 3 and 4 (Sakai et al., 1995; Sakai et al., 2000).

The floral developmental program in monocots has not been studied to the extent that it has been in dicots, although several homologs of ABC class genes have been isolated from monocot plants. Two genes homologous to AG were isolated from maize, one of the extensively studied monocot plants (Schmidt et al., 1993; Mené et al., 1995; Theissen et al., 1995). For instance, the function of one AG homologue, ZAG1, was determined by analyzing the corresponding knockout line. A loss-of-function mutant of ZAG1, zag1-mun1, has been isolated which showed loss of determinacy in the central floral whorl, but no alteration of floral organ identity (Mené et al., 1996). These studies suggest that, although the function of floral organ identity genes might have split and diverged, these genes still play important roles in flower development in monocots. As one of the class B homeotic genes, the silky1 gene of maize was revealed to be homologous to AP3 (Ambrose et al., 2000). Since the silky1 mutant shows a homeotic conversion of lodicules and stamens into palea-like organs and carpels, respectively, similar to ap3, it may indicate that the class B genes are functionally more conserved than class A and C genes among flowering plants. In rice, several MADS-box genes have also been isolated (Chung et al., 1994; Chung et al., 1995; Kang et al., 1995; Moon et al., 1999; Kyozuka et al., 2000). OsMADS3 and OsMADS4 share sequence similarity to AG and PI, respectively, and their functions were analyzed by transgenic experiments. The transgenic plants expressing antisense OsMADS3 produced lodicule-like organs in whorl 3 and several abnormal flowers in whorl 4 instead of a carpel, whereas OsMADS4 antisense plants showed transformation of stamens into carpels (Kang et al., 1998). In contrast, ectopic expression of OsMADS3 in rice caused a homeotic transformation of lodicules to stamens (Kyozuka and Shimamoto, 2002). These results show that the function of these genes, at least in part, is as predicted from the ABC model. The important role of MADS-box genes in rice flower development is further shown by the report that the leafy hull sterile (lhs1) mutant, which has a defect in the OsMADS1 gene and belongs to the AP1/AGL9 group, has abnormalities in meristem identity, organ number and organ identity (Jeon et al., 2000).

The rice flower has an architecture different from those of the two model dicot species. In general, it is believed to consist of three distinct floral organs, one gynoecium with two stigmas, six stamens, and two lodicules (Hutchinson, 1934). In order to be able to compare rice, Arabidopsis and Antirrhinum, we designate the lodicule region as whorl 2, the stamen region as whorl 3, and the carpel region as whorl 4 in this study. In rice, two bract-like organs, the palea and lemma, subtend these floral organs in an alternate arrangement. The palea is regarded as homologous to the prophyll [the first leaf produced by the axillary meristem (Arber, 1934; Dahlgren et al., 1985)], larger than the lemma and has three vascular bundles while the lemma has five. A floret consists of one gynoecium, six stamens, two lodicules, one palea and one lemma. Two empty glumes that are regarded as vestigial organs of two lower florets subtend the apical floret in an alternate arrangement. Two rudimentary glumes (the first two glumes) subtend the empty glumes. These organs form a spikelet of rice.

Several floral mutants have been described in grasses. The midribless (mbl) mutant, which has midrib-less leaves and the homeotic conversion of the gynoecium into stamens, has been reported in Panicum maximum (Fladung et al., 1991). Although the photosynthetic ability of these midrib-less leaves was analyzed in detail, the morphology of floral organs was not fully described. Similar mutants have been described in barley, ovaryless (olv) (Tsuchiya, 1962; Tsuchiya, 1969), and in pearl millet, midribless-1 (mrl-1) and mrl-2 (Rao et al., 1988), in which both the midrib and carpel differentiation are affected. The detailed floral morphology has not been described for either mutant. In rice, a similar mutation, drooping leaf (dl), was identified previously (Iwata and Omura, 1971), but the floral abnormalities have not been reported. Recently, we identified new dl alleles affecting both flower development and midrib formation. We also identified other homeotic mutants, including superwoman 1 (spw1). In this study, we describe the morphological and genetic analysis of these homeotic mutants, which led us to propose a model in which DL specifies a novel function in reproductive floral organs. The model was further supported by our molecular characterization of the SPW1 gene and expression studies.

### MATERIALS AND METHODS

#### Plant materials

Two kinds of homeotic mutants of rice (Oryza sativa L.) were used in this study. We identified two recessive alleles, superwoman1-1 (spw1-1) and superwoman1-2 (spw1-2), from M2 populations of cv. Kinnmaze and Taichung 65, respectively. Four recessive alleles of another homeotic gene, DROoping LEAF (DL), which was mapped to chromosome 3, were analyzed in this study. The dl-1 allele was first reported as a spontaneous mutation that originated in the ‘Tareba Inc’ (HO788) background (Iwata and Omura, 1971), which is designated dl-1(HO788) here. The dl-1 mutation was further introgressed into the background of Taichung 65 through several backcrosses and designated dl-1(T65) in this study. The origin of the dl-2 mutation is unknown. This mutant has been maintained at the University of Tokyo’s Experimental Farm. We identified two new mutations, dl-superman1 (dl-sup1) and dl-superman2 (dl-sup2), from MNU (N-methyl-N-nitrosourea)-treated M2 populations of cv. Taichung 65 and Kinnmaze, respectively. For the investigation on the genetic interaction of two floral homeotic genes, SPW1 and DL, the double mutant was constructed by crossing SPW1/spw1-1 heterozygotes as the female parent with dl-sup1 homozygote as the male parent. Resulting F1 plants were allowed to self-pollinate and the double mutant plants were selected from the F2 population.

#### Morphological analysis

For scanning electron microscopy (SEM), samples were fixed in 2.5% glutaraldehyde in 0.1 M sodium phosphate buffer (pH 7.2) for about 16 hours at 4°C. After they were rinsed with 0.1 M sodium phosphate buffer (pH 7.2), the samples were post-fixed in 1% osmium tetroxide for 3 hours at 4°C. Subsequently, they were rinsed with the buffer, dehydrated through a graded ethanol series, and substituted with 3-methyl-butyl-acetate. Samples were critical-point-dried, sputter-coated with platinum, and observed under the scanning electron microscope (Hitachi S-4000, Tokyo) at an accelerating voltage of 15 kV. For light microscopic observations, flowers were fixed in 2.5% glutaraldehyde for at least 16 hours at 4°C. They were dehydrated through a graded ethanol series, and then embedded in Technovit 7100 resin (Kulzer, Germany). Samples were sectioned in 4 µm and stained with 0.05% Toluidine Blue-O and observed under the light microscope (Olympus AX-80, Tokyo).
Linkage analysis and sequencing

F₂ populations were generated by the self-pollination of F₁ plants derived from the cross between SPW1/spw1-1 (Japonica cv. Kinmaze) and Kasalath (Indica). Plants homozygous for spw1-1 were selected from F₂ populations and used for linkage analysis of OsMADS16. The genomic DNA of these F₂ mutants was extracted by the proteinase K DNA extraction method (http://www.its.caltech.edu/~plantlab/html/_index.html). Genomic DNA was digested with XhoI and subjected to gel electrophoresis. The separated DNA was blotted to Nylon membrane and hybridized with DIG-labeled OsMADS16 DNA as a probe. The membrane was washed in 1× SSPE 0.1% SDS at 65°C for 1 hour and then in 0.1× SSPE 0.1% SDS at 65°C for 1 hour. Detection was carried out according to the manufacturer’s instructions (Roche Molecular Biochemicals).

To obtain genomic clones containing OsMADS16, we screened a BAC library, which was constructed in the Japonica YT14 background (Bryan et al., 2000), by PCR using primers, M16F4:AGCGTCGACTCCTTCTTGGA and A TCTTCGTGAAGACGCTC- (Molecular Dynamics, Inc.). As a reference, a DNA fragment of 2 kb-long DNA fragments were cloned into pGEM-T Easy vector (Promega). At least three clones from each PCR-amplified fragment were sequenced to determine mutations.

RNA isolation and analysis

Total RNA was extracted from 500 mg young inflorescence tissues of wild type, spw1-1 and spw1-2 as described previously (Naito et al., 1998). Poly(A) RNA was obtained using an mRNA purification kit (Amersham Pharmacia Biotech UK Limited). 1 μg of poly(A) RNA was loaded on a 1% denaturing agarose gel, which contained 1× Mops, 1.85% formaldehyde, and separated for 2 hours at 70 V. RNA was transferred on Hybond-N+ nylon membrane (Amersham Pharmacia Biotech UK Limited). Hybridization was performed at 42°C in the buffer with 5x Denhardt’s, 50% formamide, 5x SSC and 100 μg/ml herring sperm DNA. An SPW1 cDNA fragment without the MADS box domain, i.e. the fragment that covered the region between 102 aa residue and the 3′ end of the MADS box domain, was used to make a randomly primed probe with [α-32P]dCTP. After hybridization, the membrane was washed with 6x SSC for 30min twice at room temperature and then washed with 0.5x SSC at 65°C for 1 hour. Signals were detected on a phosphorimager screen (Molecular Dynainics, Inc.) and visualized on a STORM 820 scanner.

RESULTS

Phenotypes of superwoman1 mutants

A wild-type rice flower has two white lodicules at the adaxial (lemma) side in whorl 2, six stamens in whorl 3 and one gynoecium with two stigmas in whorl 4 (Fig. 1A,E). Since two alelic mutants, spw1-1 and spw1-2, showed indistinguishable phenotypes, only spw1-1 was analyzed in this study. In spw1-1 flowers, the two lodicules in whorl 2 and six stamens in whorl 3 of the wild-type flower were transformed to palea-like organs and carpels, respectively (Fig. 1B,F). The whorl 2 organs were green and elongated without trichomes, resembling paleae. In rice, the pala and lemma can be distinguished by two characters: (1) the pala has three vascular bundles and the lemma has five; (2) the pala has a membranous region of its margin that is not covered with trichomes (Fig. 2A). Although ectopic pala-like organs in spw1-1 did not develop distinctive vascular bundles, epidermal cells of these pala-like organs were narrow, elongated and rectangular, similar to cells in the marginal region of the wild-type pala (Fig. 2B,C). Therefore, lodicules appeared to be transformed into pala-like organs rather than lemmas in spw1-1. The number of ectopic pala-like organs varied: two (76%), three (16%) or four (8%) (Fig. 2D). The pala-like organs that were occasionally formed on the pala side often exhibited a carpelloid nature with frequently formed stigmatic papillae in the apical portion (Fig. 2E).

Although the carpels in whorls 3 and 4 of spw1 often produced ovaries and stigmas, they failed to produce fused and functional ovaries (Fig. 2F). The number of stigmas for each carpel varied from four to none. Frequently, nucellar tissues were formed in carpels, including whorl 3 carpels, and protruded from the ovary (Fig. 2G-I). When the nucellar tissue remained in the ovary, an ovule-like structure was often formed without producing a fully differentiated embryo sac (Fig. 2H). Occasionally, when the nucellar tissue completely protruded from the underdeveloped ovary, the ovule-like structure was not formed (Fig. 2I). When the spw1-1 carpels were crossed with wild-type pollen, there was no seed set, showing that spw1-1 carpels, including the one in whorl 4, were sterile.

Early development of wild-type and spw1 mutant flowers

In the wild-type flower, six stamen primordia start to develop just after the pala primordium has established (Fig. 3A). After stamen primordia are produced, the carpel primordium becomes enlarged (Fig. 3B). The gynoecial ridge starts to

In situ hybridization

Wild-type and mutant flowers were fixed in 3% paraformaldehyde and 0.3% glutaraldehyde for 16 hours at 4°C. They were dehydrated through a butanol series and embedded in Paraplast and sectioned at 8 μm using a rotary microtome. DIG-labeled RNA probe was synthesized from the 0.6 kb-long, 3′ region of OsMADS45 and the 0.7 kb-long, 3′ region of OsMADS16 excluding the MADS-box region, following the manufacturer’s instructions (Roche Molecular Biochemicals). Hybridization and immunological detection with alkaline phosphatase were performed according to the method of Kouchi and Hata (Kouchi and Hata, 1993). Radioactive in situ hybridization was performed as described previously (Sakai et al., 1995), with the exception that the exposure length was 6 weeks.
develop on the lemma side of the floral meristem and encloses the ovule primordium. The lemma side of the carpel protrudes to form stigmas (Fig. 3C).

In the spw1-1 flower, the shape of the six primordia of the ectopic carpels in whorl 3 was similar to that of the wild-type stamen primordia at the initial stage (Fig. 3D). Whereas wild-type stamen primordia became rectangular in shape, the six primordia in whorl 3 of the spw1-1 flower became broad, and followed the developmental course of the gynoecium (Fig. 3E). When the central gynoecium formed stigma primordia, the ectopic palea-like organs became apparent in the position of wild-type lodicules between the lemma and ectopic carpels (Fig. 3F). These results indicated that the number of organ primordia in whorl 3 was not altered, and the transformation of stamens into carpels occurred at a very early stage of floral organ development.

Phenotypes of drooping leaf mutants

Four dl mutants, which showed the drooping leaf phenotype (Fig. 4B), produced flowers with varying degrees of abnormalities in carpel formation (Table 1, Fig. 5). The blade and sheath of dl mutants failed to form the midrib and fully developed clear cells (Fig. 4D). The dl mutants appeared to produce a lateral vein at the position of the midrib of the wild-type leaf. Other leaf structures were not affected.

The dl-1 (HO788) mutant produced drooping leaves and, frequently, abnormal flowers. Although more than half of dl-1 (HO788) flowers were normal, about 40% of flowers produced a gynoecium with three or four stigmas (Table 1, Fig. 5B). Very rarely, dl-1(HO788) flowers produced staminoid carpels, in which anthers were formed apically, or ectopic stamens originated from the base of carpels. Despite these abnormalities, dl-1(HO788) plants exhibited only slightly reduced seed fertility (80.4%) comparable to the wild type (87.5%).

dl-1(T65), the introgressed dl-1(HO788) mutation in another Japonica background, affected carpel development more severely than dl-1(HO788). In dl-1(T65), the number of stigmas was increased in about 60% of flowers, and the transformation of the gynoecium into stamens or the production of ectopic stamens was detected in nearly 10% of flowers (Table 1, Fig. 5C). Occasionally, staminoid carpels, which bore anther tissues on the carpel tissue, were formed between more completely transformed ectopic stamens and the whorl 3 stamens (Fig. 5D). When two carpels were formed in dl-1 (T65) flowers, they were aligned in the lemma-palea direction. The seed fertility of dl-1(T65) (52.7%) was lower than that of dl-1(HO788).

Plants harboring the dl-2 mutation showed drooping leaves, while flowers were normal except for producing carpels with three stigmas at a low frequency (Fig. 5E, Table 1). Thus, dl-2 affects only the midrib development and rarely the carpel development, and can be considered the weakest of the four dl alleles.

The homeotic conversion of the carpel into stamens as well as the formation of drooping leaves was observed in all dl-sup1
and dl-sup2 plants (Fig. 1C,G, Fig. 5F,H, Table 1). The phenotype of dl-sup2 (Fig. 5H, Table 1) was almost the same as that of dl-sup1. In both mutants, the transformation was complete, producing no carpel. The number and position of the original stamens were not affected, and the ectopic stamens were produced in alternate arrangement in the position of the gynoecium (Fig. 5G,I). The number of ectopic stamens in dl-sup1 varied from three to seven, and the ectopic stamens were produced in the lemma-palea direction (Fig. 5G). As a result, many alternately arranged extra stamens occupied the position of the wild-type gynoecium. The ectopic stamens often had broad filaments (Fig. 5H).

We analyzed the development of dl-sup1 and dl-sup2. The primordia of six stamens in whorl 3 were normally produced in dl-sup1 flowers (Fig. 3G,J). The primordium of the first ectopic stamen emerged as a lateral protrusion on the lemma side of the floral meristem (Fig. 3H,K). When normal anthers became rectangular in shape, the first ectopic stamen primordium became broad and subtended the central apical meristem (Fig. 3K). At the stage when two stigmas were differentiated from the carpel primordium in the wild-type flower, several ectopic stamens were produced alternately, and the floral meristem at the center appeared to remain undifferentiated in the mutant flower (Fig. 3I,L).

### Interaction between SPW1 and DL
To elucidate a possible genetic interaction between SPW1 and DL, we constructed the double mutant, spw1-1 dl-sup1. The spw1-1 dl-sup1 flower showed an unexpected phenotype, which could not be explained by additive or epistatic interactions (Fig. 1D,H). Lodicules were homeotically transformed into palea-like organs in whorl 2 as in spw1-1. Interior to whorl 2, yellowish and soft organs were produced in the lemma-palea direction (Fig. 5G). As a result, many alternately arranged extra stamens occupied the position of the wild-type gynoecium. The ectopic stamens often had broad filaments (Fig. 5H).

### Table 1. Frequency of pistil abnormalities in dl mutants

<table>
<thead>
<tr>
<th>Genotype</th>
<th>No. of flowers examined</th>
<th>Normal</th>
<th>More than two stigmas</th>
<th>Two pistils*</th>
<th>Extra stamens with normal pistil†</th>
<th>Staminoid pistil‡</th>
<th>Extra stamens with no pistil§</th>
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<tbody>
<tr>
<td>Wild type</td>
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<td>50</td>
<td>0</td>
<td>0</td>
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<tr>
<td>dl-1(HO788)</td>
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<td>36</td>
<td>27</td>
<td>0</td>
<td>0</td>
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<td>1</td>
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<tr>
<td>dl-1(T65)</td>
<td>82</td>
<td>20</td>
<td>51</td>
<td>2</td>
<td>6</td>
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<td>2</td>
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<tr>
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<td>40</td>
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<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>39</td>
</tr>
</tbody>
</table>

*Two pistils were formed without altering the stamen number.
†These extra stamens were produced around normal pistil without staminoid characteristics.
‡Staminoid pistil was produced instead of or in the vicinity of the normal pistil. Extra stamens were frequently produced.
§The pistil was completely transformed to stamens.

See above for labeling shifts.
Fig. 3. Scanning electron micrographs of early developmental stages of spw1-1, dl-sup1 and dl-sup2 flowers. (A-C) Wild-type; (D-F) spw1-1; (G-I) dl-sup1; (J-L) dl-sup2. (A,D,G,J) Young flowers at the stage when organ primordia were formed in whorl 3. (B,E,H,K) Young flowers at the stage when stamen primordia have started to form the anther structure in wild type. (C,F,J,L) Flowers at the later stage when the carpel primordia start to form stigmas in wild type. (D,G,J) In spw1-1, dl-sup1 and dl-sup2 flowers, six organ primordia were formed at the positions where stamen primordia were formed in the wild type. (E) In spw1-1, six organ primordia in whorl 3 broaden to form carpels. (F) Emergence of ectopic palea-like organ primordia in spw1-1. (H,K) dl-sup1 and dl-sup2 flowers. The primordium of the first ectopic stamen (arrowhead) is developing from the lemma side of whorl 4. (I,L) At the later stage, the floral apical meristem (arrowhead) has continued to produce many ectopic stamens. le, lemma; pa, palea; ep, ectopic palea-like organ; es, ectopic stamen. Bars: 30 μm.

Fig. 4. Phenotype of dl-1(T65) plants in the vegetative phase. (A) Wild-type plant in the vegetative phase. (B) dl-1(T65) plant at the same stage with drooping leaves. (C) Transverse section of the wild-type leaf blade. The midrib (MR) in the middle of the leaf blade has large clear cells (arrowhead), and an overall structure that is distinct from that of the lateral veins (arrow). (D) Transverse section of the dl-1(T65) leaf blade that lacks a midrib. The vein in the middle of the leaf blade (arrowhead) resembles the lateral veins (arrow). Bars (C,D), 200 μm.
The ontogeny of double mutant flowers showed that the primordia in whorl 2, corresponding to lodicules in the wild type, developed into palea-like organs as in spw1-1. The six primordia corresponding to wild-type stamens in whorl 3 seemed to be normal at the beginning (Fig. 6F). However, the primordia in whorl 3 successively became broader similar to those seen in the development of spw1-1 ectopic carpels (Fig. 6G), but the subsequent development of the spw1-1 dl-sup1 flower deviated from the spw1-1 flower. In the region interior to whorl 3, the central meristem became enlarged toward the palea and lemma (Fig. 6G), and continuously produced new meristems in a medial plane (Fig. 6H), forming a number of apices (Fig. 6H). Unidentifiable organs were formed indeterminately from each meristematic apex (Fig. 6D,I).

To elucidate whether these organs were floral in nature, we analyzed OsMADS45 expression by means of in situ hybridization. OsMADS45 shares homology with Arabidopsis SEP1 (AGL2) and SEP2 (AGL4) (Pelaz et al., 2000) and was shown to be expressed in floral organs in whorl 2, 3 and 4 of wild-type flowers (Greco et al., 1997) (Fig. 7C). In order to see whether OsMADS45 is expressed specifically in flowers, we examined expression in various tissues. The expression of OsMADS45 appeared to be floral specific and was not detected in the vegetative shoot or inflorescence meristems (Fig. 7A,B). After stamen primordia started to develop, OsMADS45 was expressed in developing stamen and lodicule primordia (Fig. 7C). OsMADS45 RNA was further detected in the developing carpel (Fig. 7C) and in integuments (data not shown). In spw1 dl-sup1 flowers, the expression of OsMADS45 was not altered (Fig. 7D). OsMADS45 was expressed in organ primordia formed in whorl 2, 3 and 4. This result suggested that these organs still retain partial floral organ identity.

**Identification of the SPW1 gene**

The phenotype of spw1 mutants is similar to the ap3 and pi mutants of Arabidopsis. It has been reported that there are three homologs of B function genes in rice, OsMADS2 and OsMADS4, which are genes homologous to PI, and OsMADS16, which is homologous to AP3 (Chung et al., 1995; Moon et al., 1999). In order to examine a possible linkage of SPW1 to one of these homologs, we attempted to analyze the segregation of the spw1 phenotype with these genes, using the F2 spw1 mutants derived from the cross between spw1-1 and Indica cv. Kasalath. By analyzing RFLP associated with OsMADS16 in 30 F2 spw1-1 plants, the Japonica genotype was found to completely co-segregate with the spw1-1 allele (data not shown). Based on the tight linkage of SPW1 and OsMADS16, we examined the OsMADS16 genomic sequence of the wild type and mutants. The 4.3 kb-long OsMADS16 genomic region consisted of seven exons and six introns (Fig. 8A,B). By sequencing spw1 mutants, we identified a G to A base change at the 5¢ end of the fifth intron in spw1-1 and a G to A base change at the 5¢ end of the third intron in spw1-1 (Fig. 8A).

The effect of spw1 mutations on the SPW1 transcript was analyzed by RNA blot hybridization. Total RNA from young panicles of spw1-1, spw1-2 and the wild type was separated for the purpose, which was subsequently hybridized with a probe specific to SPW1. In the two mutants, the accumulation of SPW1 RNA was significantly reduced. Furthermore, the size
of \textit{SPW1} RNA in \textit{spw1-2} appeared to be shorter than the wild-type RNA (Fig. 8C). In order to analyze the effect of \textit{spw1} mutations more precisely, we further analyzed \textit{SPW1} RNA by using RT-PCR. The sequence of amplified DNA fragments revealed that the splicing of \textit{SPW1} RNA was affected by the mutations (Fig. 8E). In \textit{spw1-1}, the mutation occurred at the acceptor site of the third intron, leading to cryptic splicing at a position six bases downstream of the acceptor site and causing the deletion of two conserved amino acid residues in the K box (Fig. 8B). In \textit{spw1-2}, the mutation occurred at the donor site of the sixth intron and resulted in deletion of the entire fifth exon (Fig. 8B).

**Expression of the \textit{SPW1} gene**

\textit{SPW1} expression in wild-type flowers was analyzed by means of in situ hybridization using \textit{SPW1} antisense RNA as probe. \textit{SPW1} RNA started to accumulate in incipient primordia of lodicules and stamens in wild-type flowers (Fig. 9A). The strong expression of \textit{SPW1} RNA continued to be seen in stamen and lodicule primordia (Fig. 9B,C) and also in mature tissues of filaments and anthers except developing microsporophylls (Fig. 9D). No signal was detected in the gynoecium or in the lemma and the palea.

\textit{SPW1} expression was also examined in \textit{spw1} mutants. We failed in several attempts to detect reproducible signals in mutants by using the non-radioactive method, and therefore we performed in situ hybridization with a radioactive probe. After exposing the hybridized tissues for 6 weeks, we detected weak signals of \textit{SPW1} RNA in incipient organ primordia in the region of whorls 2 and 3 of \textit{spw1-1} developing flowers (Fig. 9M,N). However, shortly after organ primordia were formed in whorls 2 and 3, \textit{SPW1} RNA was not observed above the limits of detection (Fig. 9O,P).

In order to examine the relationship between \textit{DL} and \textit{SPW1} at the transcriptional level, we further analyzed the accumulation of \textit{SPW1} RNA in \textit{dl-sup1} mutant flowers. The expression pattern of \textit{SPW1} RNA in \textit{dl-sup1} flowers was indistinguishable from the wild-type expression until the stage when whorl 4 organ primordia emerged from the floral meristem (Fig. 9E). When the gynoecial ridge began to rise in the wild-type flower, \textit{SPW1} RNA was ectopically expressed in the lemma side of the whorl 4 floral meristem in \textit{dl-sup1} flowers where the first ectopic stamen primordium would arise (Fig. 9F). \textit{SPW1} RNA was further detected in the region where the second ectopic stamen arises (Fig. 9H). \textit{SPW1} expression in the whorl 4 area appears to be limited to the developing primordia, often leaving several cell layers that do not accumulate \textit{SPW1} RNA. Also, throughout the floral development, \textit{SPW1} expression was not detected in the very central region of the floral meristem of \textit{dl-sup1} (Fig. 9F-H).

**DISCUSSION**

\textit{SPW1} is a rice B function gene

We identified the \textit{SPW1} gene by mapping \textit{spw1} mutations to the AP3 homolog MADS-box gene, \textit{OsMADS16}. Both \textit{spw1-1} and \textit{spw1-2} carry mutations in the splicing acceptor-donor junctions, which cause abnormal splicing reactions and result in the deletion of part of the protein sequence. In \textit{spw1-1}, the mutation at the acceptor site of the third intron leads to cryptic splicing six bases downstream, which causes the deletion of...
Fig. 7. OsMADS45 expression in the wild type and spw1 dl-sup double mutant. (A) Wild-type vegetative shoot, (B) wild-type inflorescence shoots, (C) wild-type flower and (D) spw1-1 dl-sup1 flower (longitudinal sections). In wild type, the expression was detected in lodicules (arrowhead), stamens (st) and the carpel (ca), but not in vegetative or inflorescence shoots. In the mutant flower, the expression was detected in organs formed in whorl 2 and inner regions SAM, shoot apical meristem; le, lemma; pa, palea; st, stamen primordia. The numbers, 1 and 2, indicate the primary and secondary inflorescence meristems, respectively. Bar, 50 μm.

Implication of spw1 homeotic transformation in monocot flower evolution

The identification of SPW1 as a class B gene in rice provides insight into the floral structure of rice and other monocots. The comparison of spw1 loss-of-function phenotypes with the class B mutant phenotypes in dicots strongly suggests that lodicules are equivalent to petals and the palea-like organs formed in spw1 whorl 2 correspond to sepal, whorl 1 floral organs in dicots. This finding is very similar to what was described for the maize silky1 mutant (Ambrose et al., 2000). Our observation of spw1 whorl 2 organs being morphologically not identical to the wild-type palea might lead to two diverse interpretations. (1) The transformation of lodicules to paleae is incomplete because of the presence of residual lodicule identity in spw1, or (2) organs formed in spw1 whorl 2 are indeed the sepal-equivalent organs, which are, however, distinct from the wild-type palea and usually not formed in the wild-type floret. These organs are evident only when the class B function is missing in whorl 2. In the latter case, the palea could be considered a bract-like organ, in agreement with the general hypothesis that grass flowers lack sepals (Hackel, 1887; Arber, 1934; Dahlgren et al., 1985). The evolutionary relevance of the homology between palea and sepals remains to be explored.

DL plays an important role in vegetative and reproductive development

Based on the loss-of-function phenotype, DL has functions in two distinct developmental pathways, midrib and carpel development. Mutants similar to dl have been identified in other grass species, barley (Tsuchiya, 1962), pearl millet (Rao et al., 1988), and Panicum maximum (Fladung et al., 1991). These mutations are single and recessive, and affect both the midrib formation and carpel development. In P. maximum, the mbl mutation causes midrib-less leaves and the conversion of the gynoecium into stamens (Fladung et al., 1991). In pearl millet, at least two loci, MRL-1 and MRL-2, have been identified, both affecting midrib and carpel development (Rao et al., 1988). In barley, ovl causes the loss of midrib and the degeneration of ovary (Tsuchiya, 1962). Although the flower phenotype of these mutants has not been fully characterized except in the case of mbl of P. maximum, mrl-1, mrl-2 and ovl do not show any homologous to AP3 (Ambrose et al., 2000) exhibits a phenotype very similar to rice spw1. This also supports the notion that class B floral organ identity genes are present in monocots. Although these class B homeotic genes appear to have conserved functions in organ identity specification, other functions of these genes in flower development appear to be diverse. In spw1 mutants, the number of whorl 2 organs is more than that of the wild type. Furthermore, the spw1 mutants do not form any functional carpels even in whorl 4, resulting in complete sterility, whereas ap3 or pi mutants are female fertile. The sterility of spw1 seems to correlate with overproduction of undifferentiated nucellar tissue. It is noteworthy to mention that the Arabidopsis class B mutants, ap3 and pi, also affect cell proliferation; however, in these mutants there is a reduction of organ number in whorl 3, while whorl 2 organ number is not altered (Bowman et al., 1991; Jack et al., 1992; Sakai et al., 2000). To this extent, SPW1 appears to have a specific function in the regulation of the whorl-specific proliferation, which is distinct from AP3 and PI.
homeotic conversion of carpel into stamens. However, midribless leaves and occasional abnormal carpel development are common to all the above mutants. Since similar mutations pleiotropically affecting both leaf midrib and carpel development have not been reported in dicots, these genes appear to have a unique combination of functions in monocots. The phenotypic characteristics of four $dl$ alleles, particularly floral phenotypes, indicate that $dl-2$ is the weakest allele, which does not affect floral organ development, and $dl$-$sup1$ and $dl$-$sup2$ are the strong alleles converting the carpel into stamens. No mutants have been identified which produce normal leaves but cause homeotic conversion of the carpel into stamens. This suggests that the formation of the midrib requires more complete activity of the $DL$ gene product than the carpel development does.

The floral phenotype of strong $dl$ mutants ($dl$-$sup1$ and $dl$-$sup2$) is similar to that of superman ($sup$) mutants in Arabidopsis, which form extra stamens interior to the stamen whorl (Schultz et al., 1991; Bowman et al., 1992). It is reported that $SUP$ encodes a C2H2-type zinc-finger protein, and is expressed in the adaxial region of the whorl 3 floral meristem (Sakai et al., 1995). The function of $SUP$ is shown to be involved in co-ordinated proliferation control of whorl 3 and 4 floral meristems. However, the $dl$ flower exhibits...
several phenotypes seemingly distinct from sup. Firstly, SUP does not affect vegetative development (Schultz et al., 1991; Bowman et al., 1992; Sakai et al., 1995). Secondly, ectopically formed stamens are arranged in a different pattern. In sup mutants, the extra stamens are formed in extra whorls that exhibit a duplicated pattern of the stamen whorl (whorl 3) (Schultz et al., 1991; Bowman et al., 1992). In contrast, these extra stamens in dl-sup mutants are formed not as a duplication of whorl 3 but as a branch structure along the axis of the palea and lemma. These differences could be explained by assuming that DL acquired several new functions during its divergence away from the DL/SUP ancestral gene. Nevertheless, taking into account the interaction between DL and SPW1 as discussed below, we are tempted to consider that DL is distinct from SUP in specification of carpel identity.

**Genetic interaction between SPW1 and DL**

In order to examine potential genetic interactions between dl and spw1, we constructed the double mutant. The double mutant showed a phenotype distinct from that seen in Arabidopsis ap3 sup. The ap3 sup double mutant has a phenotype similar to ap3 (Schultz et al., 1991; Bowman et al., 1992), but the development of whorl 4 organs is suppressed, which is largely explained by an additive interaction of two mutations (Sakai et al., 2000). In the spw1-1 dl-sup1 double mutant flower, however, organs whose identities are neither carpel nor stamen are indeterminately produced in whorls 3 and 4. This phenotype again indicates that DL function is not to regulate the boundary between whorl 3 and whorl 4 but rather to provide the carpel organ identity and the whorl 4 determinacy. Furthermore, the expression pattern of OsMADS45, which we showed to be flower specific, suggests that the organs formed whorl 3 and 4 of double mutant flowers have floral organ identity.

**A model of rice flower development**

According to previous data derived from cDNA sequences and expression patterns, genes corresponding to the ABC floral homeotic genes in Arabidopsis and Antirrhinum appear to be present in rice, and their corresponding functions were partly proved by antisense experiments (Chung et al., 1994; Chung et al., 1995; Kang et al., 1995; Kang et al., 1998; Moon et al., 1999; Kyozuka et al., 2000). Two genes sharing homology to AG, OsMADS3 (also referred to as RAG) and OsMADS13, have been cloned in rice (Lopez-Dee et al., 1999; Kyozuka et al., 1998). Their expression patterns and transgenic experiments suggested that OsMADS3 is the C function gene in rice (Kang et al., 1998; Kyozuka et al., 2000; Kyozuka and Shimamoto, 2002). Also, two genes sharing homology to PI, OsMADS2 and OsMADS4, have
been cloned in rice. Based on the expression patterns in flowers, OsMADS2 and OsMADS4 are believed to be Pl homologs (Chung et al., 1995; Kyozuka et al., 2000). In the case of OsMADS4, the function has further been elucidated by anti-sense experiments (Kang et al., 1998). As for the AP3 homolog, OsMADS16 was initially isolated by screening for proteins which could interact with OsMADS4 protein (Moon et al., 1999). We show in this report that the SPW1 gene is identified as OsMADS16 and the loss of SPW1 function causes the phenotype corresponding to the class B mutant phenotype. There are several rice genes sharing sequence homology to the Arabidopsis class A gene, AP1. Among them, the LHS1 gene (OsMADS1) was shown to carry AP1 function at least in part (Jeon et al., 2000).

As discussed above, our data show that DL has a novel function that has not yet been described in other flowering plants. With regard to its function in floral organ specification, DL appears to act in whorl 4 to specify carpel identity, presumably in conjunction with other genes including class C genes (Fig. 10A). The transformation of floral organs in dl as well as spw1 mutants can be explained by the mutually exclusive interaction of both genes: the loss of DL function results in the spatial expansion of SPW1 function in whorl 4, which leads to the transformation of the gynoecium into stamens (Fig. 10B). Likewise, the loss of SPW1 function causes spatial expansion of DL function in whorl 3, which leads to the transformation of stamens into carpels (Fig. 10C). Such mutually antagonistic interaction of DL and SPW1 resembles the one between class A and C activities in Arabidopsis (Bowman et al., 1991; Drews et al., 1991). The loss of both SPW1 and DL causes the transformation of whorl 3 and 4 organs into indeterminate structures that produce organs with no apparent identity (Fig. 10D). This indicates that these two rice genes, SPW1 and DL, play an essential role in specifying floral organ identity. In Arabidopsis, genes that specify carpel identity were isolated and their interactions with ABC homeotic genes studied (Alvarez and Smyth, 1997; Alvarez and Smyth, 1999; Liu et al., 2000). These genes include LEUNIG (LUG), AINTEGUMENTA (ANT), CRABS CLAW (CRC) and SPATULA (SPT). Among them, crc and spt mutants show a significant reduction in carpelloidy in combination with the pi-1 mutation (Alvarez and Smyth, 1999). None of the loss-of-function mutants of these genes, however, exhibits a phenotype similar to dl-sup. Nevertheless, it would be interesting to see whether there is any common genetic pathways controlled by CRC/SPT in Arabidopsis and DL in rice.

Although data on DL expression is currently not available, the studies on SPW1 expression in mutants provide additional data that are consistent with the model. SPW1 expression was significantly downregulated in the spw1 mutant. Although this transcriptional repression could be due to a splicing defect, resulting in increased RNA turnover, or possible autoregulation similar to the one reported for AP3 (Jack et al., 1994), it could also be due to ectopic DL activity in the spw1 mutant background. However, ectopic SPW1 expression was detected in whorl 4 of the strong dl mutants. Ectopic expression was not detected at the stage of the initial SPW1 expression. Rather, it was seen at the later stage when whorl 3 stamen primordia started to differentiate into filament and anther structures and the whorl 4 floral meristem proliferated to form a mound. The pattern of ectopic expression again differed from what has been observed in sup mutants in Arabidopsis, where AP3 expression gradually spread into the whorl 4 area (Sakai et al., 1995). In dl-sup, ectopic expression of SPW1 occurred abruptly in part of the whorl 4 floral meristem. This also suggests that the organ identities of whorls 3 and 4 are not specified at the same stage in rice as they are in Arabidopsis. In rice, the specification of whorl 4 appears to occur after that of whorl 3. A model of sequential specification of floral organs has been discussed in other species (Hicks and Sussex, 1971). In Arabidopsis and tobacco, floral organ specification was shown not to require signals from outer whorls (Day et al., 1995). It remains to be explored whether floral whorls in rice are also autonomous and independent from each other with regard to organ specification.

According to recent report, the DL gene has been identified by implementing a map-based cloning strategy (T. Yamaguchi, Y. Nagato and H. Hirano, personal communication). Further analyses of the DL gene at the molecular level could shed more light on the unique function of DL and its interaction with other floral homeotic genes.
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REFERENCES


