Modulation of Cell Proliferation by Heterotrimeric G Protein in Arabidopsis

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The \( \alpha \) subunit of a prototypical heterotrimeric GTP-binding protein (G protein), which is encoded by a single gene (GPA1) in Arabidopsis, is a modulator of plant cell proliferation. \( \text{gpa1} \) null mutants have reduced cell division in aerial tissues throughout development. Inducible overexpression of GPA1 in Arabidopsis confers inducible ectopic cell division. GPA1 overexpression in synchronized BY-2 cells causes premature advance of the nuclear cycle and the premature appearance of a division wall. Results from loss of function and ectopic expression and activation of GPA1 indicate that this subunit is a positive modulator of cell division in plants.

Heterotrimeric G proteins regulate cell growth, differentiation, and transformation in animal cells (1). Many growth factors activate receptors that transmit signals to the cytoplasm through heterotrimeric G proteins. Of the 17 \( \Gamma \) \( \alpha \) subunits that have been cloned, 10 couple mitogenic signaling (2, 3). Studies of the interaction between \( \Gamma \) \( \alpha \) subunits and proliferation support the emerging view that the \( \alpha \) subunits form a new class of oncogenes (4–6).

The Arabidopsis genome contains a single prototypical G protein (GPA1) gene, offering a unique advantage over its animal counterparts to dissect its role in cell proliferation. Various signals such as auxin, cytokinin, brassinosteroids, light, sucrose, stress, and developmental factors modulate cell proliferation in plants as well (7). On the basis of GPA1 expression in actively dividing cells, it has been suggested that GPA1 is involved in promoting active cell division (8), a notion supported by the observation that a rice \( \Gamma \) \( \alpha \) mutant confers a dwarf phenotype (9).

By screening an Arabidopsis transferred DNA (T-DNA) insertion population (10), two recessive mutant alleles, \( \text{gpa1-1} \) and \( \text{gpa1-2} \), were identified and shown by direct sequencing to harbor T-DNA in the predicted seventh intron (11). In \( \text{gpa1-2} \) mutants, the reading frame was restored, whereas in \( \text{gpa1-1} \) mutants, the inserted DNA was transcribed from a different start site (12). Northern hybridization results showed the expected size of truncated mutant transcripts (Fig. 1C) and that the steady-state levels of the mutant transcripts were not affected in the dark. The insertion eliminates four of its five polypeptide loops required for GTP binding (13), the guanosine triphosphatase (GTPase) domain, and the effector loop. On the basis of parallel structure-function studies on animal G\( \alpha \), the Arabidopsis GPA1 mutant proteins are predicted to be nonfunctioning. Western hybridization with antiserum directed against a recombinant Arabidopsis GPA1 showed that, in the mutant lines, no G\( \alpha \) protein of any size was detected. This indicates that the T-DNA insertions in both \( \text{gpa1-1} \) and \( \text{gpa1-2} \) produce null alleles or that the truncated gene product is no longer recognizable by the antibodies to GPA1 (Fig. 1D).

\( \text{gpa1} \) mutants displayed phenotypes that were consistent with a reduction in cell division throughout development, although with contrasting effects on organ morphogenesis. In light-grown seedlings, \( \text{gpa1} \) leaf size and morphology were maintained despite fewer cells composing this organ. Compensation by increased cell size for reduced cell number during organ morphogenesis has been documented frequently (12–14), supporting the theory that the individual cell is not always the basic unit of morphogenesis in plants. However, \( \text{gpa1} \) mutants also illustrate that a reduction of cell number results in reduced hypocotyl length, providing the alternative example of morphogenesis.

Exposure of wild-type plants to light marks the start of photomorphogenic development called de-etiolation. Both \( \text{gpa1} \) mutant alleles displayed partial de-etiolation (Fig. 2). Dark-grown \( \text{gpa1} \) mutant seedlings had short hypocotyls and open hooks typical of light-irradiated seedlings, but the root and cotyledon phenotypes were dark-grown wild type (WT). Scanning electron microscopy revealed that the constitutive hook opening is due to the normal expansion of adaxial cells.
of the gpa1-1 mutant (Fig. 2, compare C and D).

The short hypocotyl of gpa1 seedlings was due to a reduced number of elongating cells (Fig. 3), indicating impaired cell division. gpa1 mutants have about 10 hypocotyl cells (Fig. 3A), compared with the typical 20 cells of the WT (Fig. 3B). The number of hypocotyl cells is established during embryogenesis, whereas hypocotyl length after germination is established almost exclusively by cell elongation (15). Maximum cell lengths in gpa1 mutants were normal, and no additional compensating cells were observed in the hook region (Fig. 2C).

Normal leaf morphogenesis is driven by cell division and expansion. Division begins at the apex of the primordium and moves basipetally ahead of a wave of cell expansion to drive the major increase in leaf area. Additional cell divisions within intercalary meristems influence leaf shape. Epidermal leaf cells of 3-week-old gpa1 mutants are significantly larger and fewer at all positions examined in the leaf (Fig. 3E). This increase in cell expansion compensates the reduction in cell division in the gpa1 mutants. The gpa1 mutants exhibit a rotundifolia-like (16) leaf shape when grown in light (Fig. 3C). Rotundifolia encodes cytochrome P450, which might be involved in brassinosteroid synthesis (17). We have found that gpa1 mutants have reduced brassinolide responsiveness (18), consistent with the phenotype of rotundifolia.

To visualize the deduced decrease in cell division, we analyzed a mitotic reporter (19, 20) in the gpa1 background. β-Glucuronidase (GUS) staining of both the apical meristems and basal cells of the first leaf was markedly reduced in gpa1 mutants compared with controls (Fig. 4). Because overall leaf expansion was slightly faster in gpa1 seedlings, comparisons were made to wild-type seedlings that were both developmentally (5-day-old) and chronologically (4-day-old) the same as gpa1 expanding leaves. Although the normal basal pattern of division in the control leaves was apparent as a discrete and intense wave of staining, this pattern was not observed in developing gpa1 leaves. Instead, weak and diffuse GUS staining in aerial tissues was consistently found. The most likely explanation of this result is that Gs of the nuclear cycle is lengthened in gpa1 cells. As expected, owing to a lack of a root phenotype, GUS staining in gpa1 roots was consistently similar to GUS staining in WS roots, indicating that Gs does not regulate proliferation in root meristems. Therefore, we view Gs as an intermediate signal element integrating signals that modulate cell division. Signals modulating division are necessarily different between root and shoot cell types (21).

Inducible, ectopic expression of GPA1 in Arabidopsis conferred inducible, ectopic cell division in multiple organs. Three homologous lines transformed with GPA1 under the control of a dexamethasone (dex)-inducible promoter showed distinctive phenotypes only after exposure to dex, whereas control plants did not display a dex-dependent phenotype (Fig. 5). The induced phenotypes showed medium to severe reduction in growth (Fig. 5, B and C) that correlated with the level of

Fig. 1. GPA1 insertion mutants. (A) T-DNA insertion sites in GPA1. LB, T-DNA left border; RB, T-DNA right border. Gray vertical boxes represent exons. The binding domain for the G, and G, subunits is indicated by the horizontal black box at the NH2-terminus. Black ovals above exons indicate the position of the polypeptide loops for GTP binding. The white oval is the putative fifth loop for GTP binding. The white horizontal box at the COOH-terminus represents the position of the putative receptor interaction domain. The asterisk represents Switch I of the GTPase domain, and the effector loop. The horizontal hatched box is Switch II. The T-DNA insert is not drawn to scale. Bar, 200 base pairs (bp). (B) Southern blot analysis with a genomic polymerase chain reaction product generated from the 3′ region of GPA1. The indicated lanes contain 10 μg of Spe I-digested genomic DNA from wild-type seedlings (lane 1), and seedlings heterozygous at gpa1-1 (lane 2), and seedlings homozygous at gpa1-1 (lane 3). (C) Northern blot analysis. The indicated lanes contain 20 μg of total RNA from WT (lane 1), gpa1-1 (lane 2), and gpa1-2 (lane 3) plants grown for 2 days in dark. A GPA1 cDNA (8) was used as hybridization probe. The mutants show truncated transcripts, as expected from their T-DNA insertion site. (D) Immunoblot analysis. Membrane proteins (20 μg) were extracted from 1-week-old, dark-grown seedlings as indicated and subjected to immunoblot analysis with a polyclonal antiserum against recombinant GPA1 as described (32).

Fig. 2. (A) Morphology of wild-type, and mutant, 2-day-old seedlings. Wild-type and mutant seedlings were grown in the dark for 2 days on 0.5× MS salts (pH 5.7), 0.8% agar, 1% sucrose plates. Wild type (middle), gpa1-1 (left), and gpa1-2 (right). Bar, 1.5 mm. (B) Effect of T-DNA insertion on the hypocotyl and root length, degree of hook opening, and cotyledon area. Standard error of the mean is based on a minimum of 10 seedlings. Closed hooks were treated as having zero degree of opening. (C and D) Scanning electron micrograph at the hook region of gpa1-1 (C) and wild type (D). Bar, 25 μm.
GPA1 expression. Each phenotype could be explained by ectopic cell division. This is most evident in the shoot epidermis, where ectopic division planes and decreased cell area in leaves overexpressing GPA1 are abundant (Fig. 5, H to K). Furthermore, overexpression of GPA1 led to excessive cell division in meristematic regions, as well as initiation of adventitious meristems (Fig. 5D).

To determine more precisely how GPA1 modulates cell division, we expressed Arabidopsis GPA1 in synchronized tobacco BY-2 cells (line designated GOX1). The DNA content was measured in synchronized cells 6 hours later, after cells were released from aphidicolin-induced arrest [Web fig. 1, A and B (22)]. The addition of auxin shifts the percentage of control cells in G2 from 15 to 60% during this time; however, synchronized GOX1 cells advance to the maximum G2 percentage in the absence of auxin. Furthermore, whereas synchronized control cells had not synthesized a cell plate 24 hours after release from aphidicolin inhibition, 50% of GOX1 cells showed a nascent cell plate during this time [Web fig. 1, C and D (22)]. The results indicate that overexpression of GPA1 leads to increased cell division by shortening G1, consistent with the lengthened G1 phase predicted by the behavior of the loss-of-function mutants. Additional support for a role for GPA1 in modulating cell division is shown with the use of Mas7, an activator of Ga. The addition of Mas7, but not the inactive analog Mas17, markedly increased DNA synthesis in control cells, consistent with the Arabidopsis and BY-2 GPA1 overexpression data [Web fig. 1 (22)].

In mammals, the βγ subunit of heterotrimeric G proteins also triggers cell proliferation, but indirectly, by way of the mitogen-activated protein kinase (MAPK) pathway (1, 2, 23–25). Because Gβγ does not change conformation upon binding to Ga (26, 27), its downstream actions are solely dependent on Ga activation and subsequent dissociation of the heterotrimeric complex (24). One interpretation of the current results is that a plant Gβ modulates cell division because activation of Ga releases sequestration of Gβγ subunits in the cell. Therefore, a possible consequence of Ga overexpression could manifest its phenotype on a MAPK pathway regulated by the Gβγ subunits. Signal transduction by auxin, a prominent modulator of plant cell division and elongation, appears to use a MAPK pathway. Activation of the MAPK cascade suppresses auxin signal transduction (28), and therefore the partial inhibition of cell division in gpa1 plants might result from Gβγ suppression of a

Fig. 3. Reduced cell division in developing hypocotyls and leaves. (A) Hypocotyl cell sizes of WT (WS ecotype) and gpa1 mutants grown for 2 days in the dark. Seedlings were cleared in chloral hydrate and observed by Nomarski microscopy. (B) Cell size as a function of the position along the hypocotyls as shown in (A) were measured with NIH Image 1.61 software. (C) Light phenotype of 3-week-old WT and gpa1 mutant leaves. Numbers above the panel indicate the leaf area (in mm²). (D) Schematic diagram showing leaf positions used to measure cell sizes. (E) Average cell sizes from areas indicated in (D) measured as described for (B) with epidermal peel of 3-week-old leaves. Open bar, gpa1-1; black bar, WT; gray bar, gpa1-2. Error bars represent the SEM of size using at least 50 hypocotyl (B) and epidermal (E) cells from six plants.

Fig. 4. Histochemical staining showing GUS activity in WT and gpa1 plants containing the mitotic reporter cyc1At-CDB-GUS. (A) WT cyc1At-CDB-GUS plants. (B) cyc1At-CDB-GUS plants in gpa1-1 background. (C) cyc1At-CDB-GUS plants in gpa1-2 background. Bar (A to C), 1 mm. Dark-grown seedlings (A to C) are 4 days old. Arrows indicate the first leaf and apical root and shoot meristems. (D and E) Higher magnification of meristem and expanding leaf of a 4-day-old [D] and 5-day-old WT (E) cyc1At-CDB-GUS. (F) gpa1-1, 2-day-old plant shown in (B). (G) gpa1-2, 2-day-old plant shown in (C). Bar (D to G), 10 μm.
MAPK pathway. Additionally, it is plausible that Gβγ release regulates a potassium channel, as shown for brain cell GIRK2 (29).

Cell division and elongation are fundamental cellular processes in the life cycle of plants. Stimuli from multiple signaling pathways become integrated at some point to modulate proliferation. Because gpa1 mutants are compromised in multiple signal transduction, GPA1 represents this point of integration for many signals. For example, ABA regulation of ion channels in guard cells is completely eliminated (20). In addition to the indirect evidence that auxin signal transduction uses GPA1, we find that gpa1 mutants are less sensitive to gibberellic acid, brassinolide, and ACC and are hypersensitive to sugars. Intuitively, multiple signaling inputs are expected to modulate proliferation because cell proliferation pathways has been identified, and how it leads to modulate proliferation. Because GPA1 represents this point of integration for many signals. For example, ABA regulation of ion channels in guard cells is completely eliminated (20). In addition to the indirect evidence that auxin signal transduction uses GPA1, we find that gpa1 mutants are less sensitive to gibberellic acid, brassinolide, and ACC and are hypersensitive to sugars. Intuitively, multiple signaling inputs are expected to modulate proliferation. Because GPA1 represents this point of integration for many signals. For example, ABA regulation of ion channels in guard cells is completely eliminated (20).

**Fig. 5.** Dex-dependent phenotypes of seedlings overexpressing GPA1 (GOX). (A) WS ecotype control seedlings grown for 7 days under continuous light with (+) 1 μM dexamethasone (dex) or without dex (−). (B) Seedling from GOX.H2 line overexpressing GPA1 grown with 1 μM dex. (Inset) Seedlings from GOX.H2 line grown with (+) or without dex (−). (D) Line GOX.D5 overexpressing GPA1 produces multiple meristems. Bar (A) 1 mm. (E) Immunoblot analysis of GPA1 in membrane fractions from control (E) and GOX.A2 lines (F), grown for 7 days in light with the indicated amount of dex. (G) Relative expression level of GPA1 normalized to a nonspecific band. Error bars represent the SEM of pixels from the bands of two independent blots quantitated by the Molecular Dynamics software. (H to K) Cellular phenotypes from the ectopic expression of GPA1 induced by 1 μM dex. Bar (H to K), 20 μm. Arrowheads indicate the position of ectopic cell divisions. Transformed lines (H to K) are indicated.

**References and Notes**

10. T-DNA-tagged Arabidopsis mutants [60,480] (31) were generated at the University of Wisconsin Knockout Arabidopsis facility (www.biotech.wisc.edu/ Arabidopsis) and screened for insertions. Primers specific for the T-DNA left-border (5′-CATTT-TATATTTACGCTTGCGAATTAC-3′) and the T-DNA right-border (5′-TGTTAAATACCTGGTGATTTCCAACATTAA-3′) were used in tandem with GUS-specific primers (forward: 5′-GACCTTGCCTGGAATTCTTGCTTTCC-3′; and reverse: 5′-CTAGCTGACATGCATGAGGACAT-3′) for identification and isolation of the mutant lines.
18. WS, gpa1-1, and gpa1-2 seedlings were grown for 2 days in the dark on various concentrations of brassinolide (BR, 0 to 10 μM). WS and gpa1 hypocotyl growth was inhibited by BR to 45% and 73% of the control lengths, respectively.
19. cyc1At-CDBGUS contains Arabidopsis cyc1At promoter and 5′ portion of the cyclin coding region fused in-frame to the reporter β-glucuronidase (GUS) gene. The fusion contains sequences encoding the cyclin destruction box (CDB). cyc1At-CDBGUS plants were crossed into gpa1 mutant plants. gpa1 mutants were selected from F1 population grown for 2 days in dark. The selected plants were allowed to grow for an additional 48 to 72 hours in light before staining. The seedlings were stained for GUS activity.
22. Supplementary data are available on Science Online at www.sciencemag.org/cgi/content/full/292/5524/2066DC1.
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