6-19-2018

A Shared Cis-Regulatory Module Activates Transcription in the Suspensor of Plant Embryos

Kelli F. Henry  
University of California - Los Angeles

Anhthu Q. Bui  
Invivata Ltd

Tomokazu Kawashima  
University of Kentucky, tomo.k@uky.edu

Robert B. Goldberg  
University of California - Los Angeles

Follow this and additional works at: https://uknowledge.uky.edu/pss_facpub

Part of the Plant Biology Commons, and the Plant Breeding and Genetics Commons

Repository Citation
Henry, Kelli F.; Bui, Anhthu Q.; Kawashima, Tomokazu; and Goldberg, Robert B., "A Shared Cis-Regulatory Module Activates Transcription in the Suspensor of Plant Embryos" (2018). Plant and Soil Sciences Faculty Publications. 100. https://uknowledge.uky.edu/pss_facpub/100

This Article is brought to you for free and open access by the Plant and Soil Sciences at UKnowledge. It has been accepted for inclusion in Plant and Soil Sciences Faculty Publications by an authorized administrator of UKnowledge. For more information, please contact UKnowledge@lsv.uky.edu.
A shared cis-regulatory module activates transcription in the suspensor of plant embryos

Kelli F. Henry,a Anhthu Q. Bui,a Tomokazu Kawashima,a,b and Robert B. Goldberga,c

*Department of Molecular, Cell, and Developmental Biology, University of California, Los Angeles, CA 90095

Contributed by Robert B. Goldberg, May 8, 2018 (sent for review April 9, 2018; reviewed by Z. Jeffrey Chen and Terry Thomas)

The mechanisms controlling the transcription of gene sets in specific regions of a plant embryo shortly after fertilization remain unknown. Previously, we showed that G564 mRNA, encoding a protein of unknown function, accumulates to high levels in the giant suspensor of both Scarlet Runner Bean (SRB) and Common Bean embryos, and a cis-regulatory module containing three unique DNA sequences, designated as the 10-bp, Region 2, and Fifth motifs, is required for G564 suspensor-specific transcription [Henry KF, et al. (2015) Plant Mol Biol 88:207–217; Kawashima T, et al. (2009) Proc Natl Acad Sci USA 106:3627–3632]. We tested the hypothesis that these motifs are also required for transcription of the SRB GA 20-oxidase gene, which encodes a gibberellic acid hormone biosynthesis enzyme and is coexpressed with G564 at a high level in giant bean suspensors. We used deletion and gain-of-function experiments in transgenic tobacco embryos to show that two GA 20-oxidase DNA regions are required for suspensor-specific transcription, one in the 5’ UTR (+119 to +205) and another in the 5’ upstream region (−341 to −316). Mutagenesis of sequences in these two regions determined that the cis-regulatory motifs required for G564 suspensor transcription are also required for GA 20-oxidase transcription within the suspensor, although the motif arrangement differs. Our results demonstrate the flexibility of motif positioning within a cis-regulatory module that activates gene transcription within giant bean suspensors and suggest that G564 and GA 20-oxidase comprise part of a suspensor gene regulatory network.

In most higher plants, embryogenesis begins with the asymmetric division of the zygote to give rise to a small apical cell and a large basal cell (1). The apical and basal cells follow distinct pathways to differentiate into an embryo proper and suspensor, respectively (2, 3). Whereas the embryo proper undergoes many developmental and morphological changes to eventually become the mature embryo within the seed, the suspensor is a terminally differentiated embryo region that degenerates as the embryo matures. Several studies have shown that different genes are expressed in the embryo proper and suspensor (4–8), but how these genes are organized into regulatory networks (9) operating in the different embryo regions remains unknown.

Previously, we began to dissect the gene regulatory networks programming early embryo development by analyzing the activation of G564, a gene encoding a protein of unknown function that is active specifically in the giant suspensors of Scarlet Runner Bean (Phaseolus coccineus) and Common Bean (Pha-

In this paper we test the hypothesis that genes with similar suspensor-specific expression patterns in giant bean suspensors utilize a shared cis-regulatory module (9) with common cis-control elements. We show that genes encoding enzymes for each step of the gibberellic acid (GA) biosynthesis pathway (15) are expressed at high levels in SRB and Common Bean globular-stage suspensors, similar to G564, suggesting that these genes are coregulated. We analyzed in detail the upstream region of one gene in the GA pathway, SRB GA 20-oxidase, and present experiments demonstrating that the GA 20-oxidase upstream region can activate suspensor transcription in globular-stage tobacco (Nicotiana tabacum) embryos. Deletion, gain-of-function (GOF), and mutation analyses in transgenic tobacco embryos showed that the GA 20-oxidase upstream region −341 to +238 is sufficient for suspensor-specific transcription and contains functional cis-regulatory elements that are also required for suspensor transcription of the SRB G564 gene (11, 14). Mutagenesis of the predicted suspensor cis-regulatory elements in the GA 20-oxidase upstream region showed that sequences similar to the 10-bp motif, Region 2 motif, and Fifth motif are required for GA 20-oxidase suspensor transcription. Our results demonstrate that the transcription of the G564 and GA 20-oxidase genes within the SRB suspensor is activated using a shared cis-regulatory module that differs in the number, spacing, and order of cis-motifs and that this cis-regulatory module may form part of a gene regulatory network that operates in giant bean suspensors shortly after fertilization.

Results

mRNAs Encoding GA Biosynthesis Enzymes Localize to the SRB and Common Bean Giant Suspensor. We carried out in situ hybridization analysis on SRB globular-stage seeds to determine the mRNA localization patterns for genes encoding enzymes in the

Significance

Little is known about how genes are expressed in different plant embryo regions. We tested the hypothesis that shared cis-regulatory motifs control the transcription of genes specifically in the suspensor. We carried out functional studies with the Scarlet Runner Bean (SRB) GA 20-oxidase gene that encodes a gibberellic acid (GA) hormone biosynthesis enzyme and is expressed specifically within the suspensor. We show that cis-regulatory motifs required for GA 20-oxidase transcription within the suspensor are the same as those required for suspensor-specific transcription of the SRB G564 gene, although motif number, spacing, and order differ. These cis-elements constitute a control module that is required to activate genes in the SRB suspensor and may form part of a suspensor regulatory network.


Reviewers: Z.J.C., University of Texas at Austin; and T.T., Texas A&M University.

The authors declare no conflict of interest.

This open access article is distributed under Creative Commons Attribution-NonCommercial-NoDerivatives License 4.0 (CC BY-NC-ND).

1Present address: Inivate Ltd, Research Triangle Park, NC 27560.

2Present address: Department of Plant and Soil Sciences, University of Kentucky, Lexington, KY 40546.

3To whom correspondence should be addressed. Email: bbg@ucla.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1805802115/-/DCSupplemental.

Published online June 4, 2018.
GA biosynthesis pathway (Fig. 1 F–K). We observed that mRNAs encoding six enzymes leading to the synthesis of bioactive GA (ent-kaurene synthase A, ent-kaurene synthase B, ent-kaurene oxidase, ent-kaurenioic acid hydroxylase, GA 20-oxidase, and GA 3-oxidase) accumulated primarily in the giant suspensor region (Fig. 1 F–K). This extends previous studies that showed SRB suspensors are a rich source of GA (16), synthesize GA in cell-free extracts (17, 18), and contain GA 3-oxidase mRNA (6, 19).

We confirmed our SRB GA mRNA localization studies and expanded them to the closely related Common Bean by using (i) laser-capture microdissection technology to collect SRB and Common Bean globular-stage embryo proper and suspensor regions, (ii) RNA-sequencing (RNA-seq) for transcriptome profiling, and (iii) the Common Bean as a reference genome [Gene Expression Omnibus (GEO) accession no. GSE57537]. Numbers indicate average reads per kilobase per million of two biological replicates. Each panel depicts an 8-kb window including the gene structure. Black boxes represent exons. Black lines represent UTRs and introns. Arrows indicate the transcription start site. bc, basal cells; ep, embryo proper; h, hypophysis region; Pc, P. coccineus; Pv, P. vulgaris; s, suspensor. (Scale bars: 50 μm.) The images in B and D are reproduced from ref. 10. The image in E is reproduced from ref. 12. Copyright American Society of Plant Biologists, www.plantcell.org.

Fig. 1. Localization of GA biosynthesis pathway enzyme mRNAs in SRB and Common Bean embryos. (A) SRB flower. (B) Plastic section of SRB globular-stage embryo. (C) Common Bean flower. (D) Paraffin section of Common Bean globular-stage embryo. (E) Localization of G564 mRNA in a SRB globular-stage embryo. (F–K) In situ localization of GA biosynthesis enzyme mRNAs in globular-stage SRB seeds: ent-kaurene synthase A (F), ent-kaurene synthase B (G), ent-kaurene oxidase (H), ent-kaurenioic acid hydroxylase (I), GA 20-oxidase (J), and GA 3-oxidase (K). Photographs were taken using dark-field microscopy. (L–Q) Genome browser views of RNA-seq coverage of ent-kaurene synthase A (L), ent-kaurene synthase B (M), ent-kaurenioic acid hydroxylase (N), ent-kaurenioic acid hydroxylase (O), GA 20-oxidase (P), and GA 3-oxidase (Q) in SRB and Common Bean globular-stage suspensor and embryo proper regions. RNA-seq data were taken from GEO accession no. GSE57537. Numbers indicate average reads per kilobase per million of two biological replicates. Each panel depicts an 8-kb window including the gene structure. Black boxes represent exons. Black lines represent UTRs and introns. Arrows indicate the transcription start site. bc, basal cells; ep, embryo proper; h, hypophysis region; Pc, P. coccineus; Pv, P. vulgaris; s, suspensor. (Scale bars: 50 μm.) The images in B and D are reproduced from ref. 10. The image in E is reproduced from ref. 12. Copyright American Society of Plant Biologists, www.plantcell.org.

Fig. 2. Consensus sequences for suspensor 10-bp motif, Region 2 motif, and Fifth motif. Consensus sequences were generated from G564 DNA sequences shown to be required for transcription within the suspensor (11, 14).
indicate that the synthesis of bioactive GA within giant bean suspensors (16) is primarily due to the spatially restricted accumulation of GA biosynthesis enzyme mRNAs.

We examined the temporal mRNA accumulation pattern of GA 20-oxidase during early SRB embryo development (Fig. 3 A–E). GA 20-oxidase mRNA was first detected in the basal cell of a two-cell embryo shortly after fertilization and then accumulated to high levels in the suspensor from the preglobular stage to the heart stage (Fig. 3 B–E), similar to our observations for G564 mRNA (12). Later, GA 20-oxidase mRNA accumulated within the epidermis of the heart-stage embryo proper (Fig. 3E).

The temporal accumulation pattern of GA 3-oxidase mRNA in SRB embryos (Fig. 4) was indistinguishable from that of GA 20-oxidase mRNA (Fig. 3 B–E) and G564 mRNA (12). These results suggest that genes encoding GA biosynthesis enzymes are regulated by the same cis-regulatory elements as G564 and form part of a SRB suspensor gene regulatory network that is activated shortly after fertilization. To test this hypothesis, we used transgenic tobacco embryos to search for cis-regulatory elements required for GA 20-oxidase transcription within the SRB suspensor, similar to the approach that we used for G564 (11, 12, 14).

**SRB GA 20-Oxidase mRNA Accumulates Within the Suspensor of Transgenic Tobacco Embryos.** We transformed tobacco (Fig. 3F) with a 7.271-kb SRB GA 20-oxidase genomic fragment (Fig. 3G) and localized GA 20-oxidase mRNA in transgenic globular-stage embryos using in situ hybridization (Fig. 3 H and I). The GA 20-oxidase 5' and 3' regions were 4,509 and 596 bp in length, respectively, and did not contain similarity to any known genes. SRB GA 20-oxidase mRNA localized within the tobacco suspensor and embryo proper protodermal cells, the precursors to heart-stage epidermal cells (Fig. 3 H and I), similar to the pattern of GA 20-oxidase mRNA accumulation in SRB embryos (Fig. 3E). These results indicate that the pattern of GA 20-oxidase mRNA accumulation is conserved during early embryo development in both tobacco and SRB.

**GA 20-Oxidase Expression Within the Suspensor Is Under Transcriptional Control.** We introduced a chimeric SRB GA 20-oxidase/β-glucuronidase (GUS) gene into tobacco (Fig. 3J) and localized GUS enzyme activity in transgenic embryos to study GA 20-oxidase transcriptional regulation (Fig. 3 K–M). The GA 20-oxidase region −4,509/+238 fused to GUS (D-4509) (Fig. 3J) first programmed GUS enzyme activity within the basal region of the two-cell tobacco embryo, followed by the entire suspensor at the preglobular stage, and then to the globular-stage embryo proper (Fig. 3 K–M). The GUS activity pattern was consistent with the localization of GA 20-oxidase mRNA in tobacco embryos driven by the entire GA 20-oxidase gene (Fig. 3 H and I), as well as that seen during SRB embryo development (Fig. 3 B–E). These results indicate that (i) the temporal and spatial expression pattern of GA 20-oxidase is controlled primarily at the transcriptional level by sequences within the −4,509/+238 region (Fig. 3J) and (ii) the

---

**Fig. 3.** GA 20-oxidase mRNA localization in SRB embryos and GA 20-oxidase transcriptional activity during tobacco embryogenesis. (A) SRB flower (image also in Fig. 1A). (B–E) Localization of GA 20-oxidase mRNA in developing SRB embryos: two-cell stage (B), preglobular stage (C), globular stage (D) (image also in Fig. 1J), and heart stage (E). (F) Tobacco flower. (G) Conceptual representation of the SRB GA 20-oxidase transgene introduced into tobacco. Dark-blue boxes represent exons. Light-blue boxes represent UTRs and introns. Numbers indicate positions relative to the transcription start site (+1). (H and I) Hybridization of SRB GA 20-oxidase antisense (H) and sense (I) probes to globular-stage transgenic tobacco embryos. (J) Conceptual representation of the GA20-oxidase/GUS transgene introduced into tobacco. (K–M) GUS activity in transgenic tobacco embryos: two-cell stage (K), preglobular stage (L), and globular stage (M). Photographs were taken after 24-h GUS incubation for the two-cell and preglobular stages and after 1-h incubation for the globular stage. a, apical cell; b, basal cell; ep, embryo proper; s, suspensor; sy, synergid. (Scale bars: 50 μm.)

---


ES826 | www.pnas.org/cgi/doi/10.1073/pnas.1805802115
regulatory apparatus that controls GA 20-oxidase gene activity during early embryo development is conserved between SRB and tobacco.

The GA 20-Oxidase Upstream Region Contains Separate Embryo Proper and Suspensor cis-Regulatory Regions. We generated 5′ deletions of the GA 20-oxidase −4,509 to +238 region and analyzed GUS activity in transgenic tobacco embryos to identify the sequences required for transcription in the globular embryo (Fig. 5). Progressively deleting sequences from −4,509 to −275 first caused a loss of GUS activity in the embryo proper followed by loss of GUS activity in the suspensor (Fig. 5), indicating that there are separate embryo proper (−2,000 to −1,500) and suspensor (−450 to +238) cis-regulatory regions. The −450 to +238 GA 20-oxidase region appears to contain all the sequences required for transcription within the suspensor. Deletion to −275 reduced suspensor GUS activity to a barely detectable level, similar to that observed in the GUS-only negative control, which may be due to a low level of cryptic transcripts initiatiing in the vector sequence and reading through the reporter gene, as has been demonstrated for other plasmids (21). We conclude that sequences in the 175-bp region from −450 to −275 are required for suspensor transcription, although additional downstream sequences to +238 might also be required.

G564 Suspensor cis-Control Motifs Are Present in the GA 20 Oxidase −450 to +238 Region. Because GA 20-oxidase has the same suspensor-specific expression pattern as G564 (Fig. 1 E and J) (12), we searched the GA 20-oxidase −450 to +238 region for the presence of known suspensor cis-regulatory elements that activate G564 transcription: (i) the 10-bp motif (5′-GAAA-AGCGAAG-3′ with up to three nonadjacent mismatches), (ii) the Region 2 motif [5′-TTG(A/G)(A/G)(A/T)AAT-3′], and (iii) the Fifth motif [5′-(A/G)AGTTA-3′] (14). Within the −450 to +238 region we identified eight predicted 10-bp motifs, three predicted Fifth motifs, and six Region 2 motifs, allowing for one mismatch [except that the third nucleotide was not an A, as this nucleotide inactivates the Region 2 motif (11)] (Fig. 6A).

The GA 20-Oxidase Upstream Region −341 to −316 Is Required for Suspensor Transcription. To determine which of the predicted G564 motifs might be required for GA 20-oxidase suspensor transcription, we performed additional 5′ deletions within a GOF construct containing the GA 20-oxidase −450 to +238 upstream region fused to a Cauliflower Mosaic Virus (CaMV) 35S minimal promoter and GUS (GOF1) (Fig. 6A). This construct programmed high levels of GUS activity specifically within the suspensor (Fig. 6A), as predicted from our initial 5′ deletion analysis (Fig. 5), confirming that all the sequences required for GA 20-oxidase suspensor transcription are present within the −450 to +238 region. Deletions to −360 (GOF2) and −341 (GOF3) did not affect GUS activity, whereas deletion to −316 (GOF4) decreased GUS activity significantly within the suspensor (Fig. 6A). Together, these data show that the region −341 to −316 is required for full transcriptional activity in the suspensor and contains two predicted Fifth motifs, which may be functional.

The GA 20-Oxidase Upstream Region +119 to +238 Is Required for Suspensor Transcription. To determine whether sequences downstream of −341 to −316 are also required for GA 20-oxidase suspensor transcription, we performed 3′ deletions of the −450 to +238 GOF1 construct (Fig. 6B). A 3′ deletion to +119 or half of the 5′ UTR (GOF6) resulted in a significant decrease in GUS activity (Fig. 6B), indicating that sequences in the +119 to +238 GA 20-oxidase region were required for suspensor transcription. Further 3′ deletion (GOF7), did not significantly affect GA 20-oxidase suspensor transcription (Fig. 6B). We conclude that one or more suspensor cis-regulatory elements are present within the +119 to +238 region, which includes three predicted 10-bp motifs and one predicted Region 2 motif (compare GOF5 and GOF6 in Fig. 6).
decrease in suspensor transcription, similar to the level of GUS activity observed when the +119 to +238 region containing this motif was deleted (GOF6) (Fig. 7). This result indicates that the Region 2 motif is required for GA 20-oxidase suspensor transcription.

To determine whether the three predicted 10-bp motifs within this region were also required, we mutated and deleted these motifs (M2 and GOF8) (Fig. 7). Both mutation (M2) and deletion (GOF8) of the three predicted 10-bp motifs decreased GUS activity significantly (Fig. 7), indicating that at least one or more of the three 10-bp motifs is required for suspensor transcription (Fig. 7). We hypothesized that the proximal 10-bp motif (Fig. 7, yellow arrow) was required because it most closely resembled the consensus G564 10-bp motif, having only two mismatches instead of three. However, neither mutation (M3) nor deletion (GOF9) of this 10-bp motif affected GUS activity (Fig. 7). We conclude that at least one or both of the remaining 10-bp motifs in the +129 to +205 region are required for suspensor transcription.

Because the G564 suspensor cis-regulatory module requires three copies of the 10-bp motif (14), we asked whether any predicted 10-bp motifs in the region upstream of +129 was also required for GA 20-oxidase suspensor transcription. Mutating the remaining five predicted 10-bp motifs (M4) had no effect on suspensor GUS activity (Fig. 7), indicating that probably both 10-bp motifs in the +129 to +205 UTR region are required for GA 20-oxidase suspensor transcription in addition to the Region 2 motif.

The Fifth Motif and an Additional Region 2 Motif Are Required for GA 20-Oxidase Suspensor Transcription. Two Fifth motifs were predicted in the −341 to −316 GA 20-oxidase upstream region, which was also required for suspensor transcription (compare GOF3 and GOF4) (Figs. 6A and 8A). Site-directed mutagenesis was performed within the GOF2 construct to determine whether these predicted Fifth motifs at −336 to −341 and −329 to −324 were functional (Fig. 8B). Mutation of both predicted Fifth motifs in this region by either transversional mutagenesis (M5) or adenine substitution (M6) did not affect suspensor GUS activity (Fig. 8B). Because (i) the −341 to −316 region was required for suspensor transcription (compare GOF3 and GOF4) (Figs. 6A and 8A) and (ii) a Fifth motif is essential for G564 suspensor transcription (14), we searched the −341 to −316 region again for a Fifth motif allowing for one mismatch at any position in the consensus sequence (Fig. 2). We identified an additional Fifth motif that overlapped a predicted Region 2 motif in the opposite orientation (marked by an asterisk in GOF2 at −317 to −312 in Fig. 8B). Previously, we showed that G564 motif orientation did not affect suspensor transcription (11).
To determine whether the Fifth motif at −317 to −312 was required for GAs 20-oxidase suspensor transcription, site-directed mutagenesis was performed on the GOF2 construct (M7) (Fig. 8B). To mutate the Fifth motif and leave the overlapping Region 2 motif intact, we had to replace the predicted Region 2 motif at −309 to −316 (5′-TTGTAAT-3′) with the functional Region 2 motif from the 5′ UTR (5′-TCTTATAT-3′), which had a slightly different sequence (M7) (Fig. 8B). This caused a mutation (red nucleotides in Fig. 8F) in the overlapping predicted Fifth motif while keeping the Region 2 motif intact (M7) (Fig. 8B). Mutation of all three predicted Fifth motifs in the −341 to −316 region (M7) resulted in a significant decrease in suspensor transcription (Fig. 8F), consistent with the results of GOF4 that deleted the −341 to −316 region, including the first nucleotide of the −317 to −312 Fifth motif (Figs. 6A and 8A). Because mutating the two predicted Fifth motifs at −336 to −341 and −329 to −324 had no effect on suspensor GUS activity (M5 and M6) (Fig. 8B), the Fifth motif at −317 to −312 is required for suspensor transcription.

To determine whether the overlapping predicted Region 2 motif at −309 to −316 was also required for GAs 20-oxidase suspensor transcription, we mutated this motif within the GOF2 construct by changing the third nucleotide (−311) from G to A, leaving the Fifth motif intact (M8) (Fig. 8F). Previously, we demonstrated that this mutation renders the Region 2 motif nonfunctional in the G564 suspensor cis-regulatory module (11). Similar to G564, mutating a single nucleotide in the Region 2 motif at −309 to −316 (M8) abolished suspensor GUS activity (Fig. 8B). Thus, the Region 2 motif at −309 to −316, in addition to the Region 2 motif within the 5′ UTR, is required for suspensor transcription. Together, these results indicate that both the Fifth motif and the Region 2 motif in the −317 to −309 GAs 20-oxidase upstream region are essential for transcription within the suspensor and explain the loss of suspensor GUS activity using the −275 deletion (D-275) and GOF5 constructs (Figs. 5, 6A, and 8A).

Fig. 8. GUS activity in transgenic tobacco embryos containing 5′ deletions (A) and site-directed mutations (B) within the GA 20-oxidase −341 to −309 region. (A) The 5′ GOF deletion constructs are reproduced from Fig. 6A for comparative purposes. (B) Mutated constructs focusing on the −341 to −309 region. The sequence of the −341 to −309 region of each construct is shown to the left of each embryo. A conceptual representation of the predicted motifs in this region is shown in the dotted box to the left of the sequence. Region 2 and Fifth motif sequences are highlighted in purple and blue, respectively. The Region 2 motif sequence located in the 5′ UTR is shown above the GOF2 construct in pink. Arrows indicate the motif sequence orientation. Mutation sequences are shown in red font. The Fifth motif at −317 to −312 has one mismatch relative to the G564 consensus sequence (14). Yellow and green arrows, purple ovals, and blue ovals represent the 10-bp motif, Region 2, and Fifth motifs, respectively. Asterisks indicate the motifs found to be required for suspensor transcription. The dark-blue arrow represents the GUS gene. Light-blue boxes represent the GA 20-oxidase 5′ UTR. The green box represents the CaMV 35S minimal promoter. Numbers indicate positions relative to the GA 20-oxidase transcription start site (+1). Expression levels were categorized as described previously (11, 14). +++ in the Expression column indicates that suspensor GUS activity was strong; that is, the majority of the suspensors with GUS activity at 24 h were GUS-positive at 2 h. −−− in the Expression column indicates that suspensor GUS activity was weak; that is, the majority of the suspensors with GUS activity at 24 h were GUS-negative at 2 h. A minus sign (−) in the Expression column indicates no detectable suspensor GUS activity at 24 h. Numbers in the Lines column indicate the number of individual transformants displaying suspensor GUS activity over the total number of individual transformants analyzed. Numbers in the Suspensors column indicate the number of embryos displaying suspensor GUS activity at 24 h incubation over the total number of embryos analyzed. The GOF2 deletion construct is reproduced from Fig. 6A for comparative purposes. Photographs were taken after GUS incubation for 24 h. (Scale bars: 50 μm.)

To determine whether the Fifth motif at −317 to −312 was required for GAs 20-oxidase suspensor transcription, site-directed mutagenesis was performed on the GOF2 construct (M7) (Fig. 8B). To mutate the Fifth motif and leave the overlapping Region 2 motif intact, we had to replace the predicted Region 2 motif at −309 to −316 (5′-TTGTAAT-3′) with the functional Region 2 motif from the 5′ UTR (5′-TCTTATAT-3′), which had a slightly different sequence (M7) (Fig. 8B). This caused a mutation (red nucleotides in Fig. 8F) in the overlapping predicted Fifth motif while keeping the Region 2 motif intact (M7) (Fig.
cis-regulatory motifs to be activated within the suspensor region (Fig. 9).

The SRB GA 20-Oxidase Upstream Region Is Organized into Different Modules That Direct Expression to the Suspensor and Embryo Proper. GA 20-oxidase contains two discrete regions that activate transcription in the suspensor and embryo proper during embryogenesis (Figs. 5 and 9). One region (~341 to +238) activates transcription within the suspensor following fertilization (Fig. 6A). The second region (~2,000 to ~1,500) activates transcription later in embryo development within embryo proper epidermal cells (Fig. 5). This bimodal distribution of suspensor and embryo proper control regions is similar to that of G564, except that the spatial distribution of these modules differs (Fig. 9) (11, 12).

The GA 20-oxidase suspensor module activates transcription uniformly over all cells of the entire suspensor, in contrast with the cell-specific embryo proper module (Fig. 5). Our deletion and mutagenesis experiments with the ~341 to +238 suspensor control region (Figs. 5–8) did not uncover subregions required for transcription within specific suspensor cell types, such as (i) the hypophysis adjacent to the embryo proper that is derived from the embryo apical cell and (ii) the enlarged basal cell that forms connections with the seed coat and is derived from the embryo basal cell. This suggests that the GA 20-oxidase gene is activated within suspensor cells using the same regulatory processes, irrespective of position or cell lineage.

The GA 20-oxidase suspensor control region activates transcription within the basal cell of the two-cell embryo (Fig. 3 B and K) and in all suspensor cells by the late globular stage of development (Fig. 3 B–D and K–M). We did not observe any shift in this temporal sequence of transcriptional events in our deletion and mutagenesis experiments, nor did we observe any ectopic activation of transcription within the globular-stage embryo proper region by deleting or mutating parts of the suspensor control module (Figs. 5–8). These results suggest the absence of both temporal and negative cis-regulatory elements within the suspensor regulatory region. Thus, the regulation of GA 20-oxidase within the SRB suspensor is controlled by positive elements that activate transcription shortly after fertilization and within daughter suspensor cells as they form during embryogenesis.

The organization of regulatory sequences within the GA 20-oxidase suspensor control region is relatively simple compared with those that activate the transcription of storage protein genes within the mature embryo proper. Storage protein gene embryo-proper control regions contain (i) territory-specific modules regulating transcription within embryo-proper subregions, such as the axis and cotyledons [e.g., Kti3 (2) and β-Phaseolin (24)], (ii) temporal cis-regulatory elements [e.g., β-Phaseolin (24) and β-conglycinin (25)], and (iii) repressor elements [e.g., Glycinin (26) and β-Phaseolin (24)]. This difference in regulatory architecture most likely results from the suspensor being a highly specialized, terminally differentiated embryonic region with few distinct cell types that degenerates later in development, in contrast with the more complex embryo proper that contains many functionally distinct embryonic territories that give rise to the mature plant following seed germination.

At Least Five cis-Regulatory Elements Are Required to Activate GA 20-Oxidase Suspensor Transcription. Within the SRB GA 20-oxidase ~341 to +238 suspensor control region, we identified 17 short sequences similar to the motifs that are required to activate G564 in the suspensor: the 10-bp motif, the Region 2 motif, and the Fifth motif (Figs. 2 and 6) (11, 14). Deletion and site-directed mutagenesis experiments demonstrated that only five of these sequences are functional and required for GA 20-oxidase suspensor transcription—two Region 2 motifs, a Fifth motif, and two 10-bp motifs—demonstrating, in support of our original hypothesis, that both G564 and GA 20-oxidase utilize the same suspensor cis-control elements (Figs. 7 and 8). All five of these motifs are conserved at similar positions within the Common Bean GA 20-oxidase gene region (SI Appendix, Fig. S1). The remaining candidate motifs are not required for suspensor transcription (Figs. 7 and 8), illustrating the need to functionally dissect cis-regulatory modules to

![Fig. 9. Models of SRB GA 20-oxidase and G564 suspensor cis-regulatory module organization.](image-url)

understand how they operate rather than relying solely on motif similarity from computer predictions.

The Fifth motif and Region 2 motif in the GA 20-oxidase −317 to −309 upstream region overlap (Figs. 8B and 9), and mutating either motif without disrupting the other leads to a decrease or complete loss of suspensor transcriptional activity (Fig. 8B). This type of regulatory element organization is not without precedent, as functional overlapping motifs have been identified in several animal enhancer regions (27–29). By contrast, two 10-bp motifs and a second Region 2 motif are located in the GA 20-oxidase 5′ UTR and do not overlap (Fig. 9). Other plant genes contain positive transcriptional control elements in their 5′ UTRs (30, 31). Together, these data indicate that transcription factors must bind to motifs that reside both upstream and downstream of the transcription start site within the regulatory module to activate GA 20-oxidase transcription in the suspensor.

**Suspensor-Specific Gene Transcription Is Generated by a Flexible Arrangement of cis-Regulatory Motifs.** The results presented here showing the organization of the GA 20-oxidase suspensor cis-regulatory module and those carried out previously with G564 (11, 14) provide a unique opportunity to compare the architecture of two suspensor cis-regulatory modules. The G564 suspensor module is composed of three 10-bp motifs, a Region 2 motif, and a Fifth motif, all tightly clustered within a 47-bp DNA region with little spacing between motifs (Fig. 9) (14). The G564 suspensor cis-regulatory module is repeated five times in the G564 upstream region, and each repeat is able to function individually, except for repeat five, as it lacks an intact Region 2 motif (Fig. 9) (11, 14).

By contrast, the single GA 20-oxidase suspensor module is larger, 579 bp in length, and is composed of two 10-bp motifs, two Region 2 motifs, and a Fifth motif divided between the upstream and 5′ UTR regions (Fig. 9). Thus, the number, order, and spacing of the suspensor motifs differ between the G564 and GA 20-oxidase cis-regulatory modules even though they lead to the same output—suspen sor-specific transcription within the early plant embryo. This suggests that the suspensor cis-regulatory module most closely resembles a billboard-type model of control-element organization in which motif positions can vary among genes that program transcription to the same developmental state, compared with an enhanceosome-type model that requires fixed motif positions for similarly similar transcription factors. The interaction of the 10-bp motif is not represented in the DAP-seq database or other plant transcription factor databases and remains unknown (Fig. 9).

Together, the data presented here and elsewhere (11, 12, 14) demonstrate that the SRB G564 and GA 20-oxidase genes are activated transcriptionally within the suspensor by the same cis-regulatory module. This strongly suggests that G564, GA 20-oxidase, and, most likely, other genes in the GA biosynthesis pathway (Fig. 1) form part of a suspensor genetic regulatory network. The precise nature of this regulatory network and how it is activated specifically within the embryo basal region shortly after fertilization remain to be determined.

**Materials and Methods**

**Plant Materials.** Plants of the day-neutral SRB cultivar “Hammond’s Dwarf Red Flower” (Vermont Bean Seed Company) were grown in a greenhouse as described previously (12). Open flowers were pollinated by hand using a watercolor brush. Hand-pollinated flowers were tagged, and seeds were harvested 2–8 d after pollination (DAP), as described previously (12). Common Bean seeds (Andean common bean inbred landrace accession G19833) were obtained from Phillip E. McLean at North Dakota State University, Fargo, ND. Common Bean plants were grown under the same conditions as SRB plants for 1 mo and then were moved to a growth chamber with an 8-h/16-h light/dark cycle to induce flowering. Seeds 1.6–2.0 mm in length were collected at 5–6 DAP.

**Radioactive in Situ Hybridization Analysis.** Radioactive in situ hybridization studies were performed as described previously (12). Briefly, SRB seeds were harvested 2–8 DAP, and seeds were cut at their chalazal ends before fixing to enhance penetration of the fixative. SRB seeds were fixed overnight at 4 °C in 1% glutaraldehyde, 0.1 M sodium phosphate buffer (pH 7.0), and 0.1% Triton X-100. Fixed seeds were dehydrated, cleared, and embedded in paraffin. Eight-micrometer sections were hybridized with 32P-labeled anti-sense RNA probes. Probes were generated from cDNA clones made from microdissected DAP suspensor regions of globular-stage SRB embryos (12). These cDNA clones corresponded to Common Bean GA biosynthesis enzyme genes: ent-kaurene synthase A (Phvul.001G152100), ent-kaurene synthase B (Phvul.005G048500), ent-kaurene oxidase (Phvul.005G183600), ent-kaurenoic acid hydroxylase (Phvul.006G123500), GA 20-oxidase (Phvul.010G087500), and GA 3-oxidase (Phvul.010G097100). After hybridization and emulsion development, sections were stained with 0.05% toluidine blue in 0.05% borate solution. Photographs were taken using dark-field illumination with a compound microscope (Olympus BH2; Olympus Corp.). The photographs were digitized, adjusted for optimum silver grain resolution using the KPT-Equalizer program (Metacreations Corp.), and assembled in Adobe Photoshop CS5.1. Probe sequences are listed in SI Appendix, Table S2.
Nonradioactive in Situ Hybridization Analysis. Nonradioactive in situ hybridization and transgenic tobacco embryos was carried out using digoxigenin-labeled riboprobes (36). Briefly, transgenic tobacco seeds were harvested at 10 DAP and were fixed overnight at 4 °C in 10% formalin/5% acetic acid/50% ethanol (37). Fixed seeds were dehydrated, cleared, and embedded in paraffin using a Leica ASP300 S Tissue Processor. Six-micrometer sections were hybridized to sense or antisense digoxigenin-labeled riboprobes overnight. Probes were generated from a GA 20-oxidase cDNA clone containing the region +182 to +2,166, which was isolated from microdissected suspensor regions of 6-DAP globular-stage SRB embryos (12). Photographs were taken using bright-field illumination with a compound microscope (Leika 5000 B).

Bright-Field Microscopy. SRB and Common Bean seeds were fixed overnight at 4 °C in 1% glutaraldehyde, 0.1 M sodium phosphate buffer (pH 7.0), and 0.1% Triton X-100. Fixed seeds were dehydrated and cleared. SRB seeds were embedded in Spurr’s plastic resin (Polysciences) (38). One-micrometer sections were stained for 18–20 min at 42 °C with 0.05% toluidine blue in 0.05% borate solution. Photographs were taken using bright-field illumination with a compound microscope (Leika 5000 B). Common bean seeds were embedded in paraffin. Six-micrometer sections were stained for 1.5 min at 42 °C with 0.1% toluidine blue. Photographs were taken using bright-field illumination with a compound microscope (Leika 5000 B).

Plant Transformation. Tobacco (N. tabacum cultivar SR1) plants were transformed and regenerated using the leaf disk procedure (39). Each individual transformant was checked for transfer DNA (T-DNA) insertion by PCR and/or sequencing analysis. At least six independent transformants were generated for each construct. A total of 27 different constructs and 193 individual tobacco transformants were generated to carry out this study.

GUS Histochemical Assay. Transgenic tobacco seeds were harvested at 8 DAP. Globular-stage embryos were hand-dissected from seeds and assayed for GUS activity after 1, 2, and 24 h at 37 °C, as described previously (11). Embryos were photographed under bright-field illumination using a compound microscope (Leika 5000 B). T1 seeds from GUS-negative lines were tested for GUS activity following 1, 2, and 24 h at 37 °C, as described previously (11). Embryos were photographed under bright-field illumination using a compound microscope (Leika 5000 B). T1 seeds from GUS-negative lines were tested for GUS activity after 1, 2, and 24 h at 37 °C, as described previously (11). Embryos were photographed under bright-field illumination using a compound microscope (Leika 5000 B). T1 seeds from GUS-negative lines were tested for GUS activity after 1, 2, and 24 h at 37 °C, as described previously (11). Embryos were photographed under bright-field illumination using a compound microscope (Leika 5000 B).


37. Henry et al. *PNAS* | vol. 115 | no. 25 | E5833


