Activation of the knirps locus links patterning to morphogenesis of the second wing vein in Drosophila

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Accepted 3 October 2002

SUMMARY

The adjacent knirps (kni) and knirps-related (knrl) genes encode functionally related zinc finger transcription factors that collaborate to initiate development of the second longitudinal wing vein (L2). kni and knrl are expressed in the third instar larval wing disc in a narrow stripe of cells just anterior to the broad central zone of cells expressing high levels of the related spalt genes. Here, we identify a 1.4 kb cis-acting enhancer element from the kni locus that faithfully directs gene expression in the L2 primordium. We find that three independent ri alleles have alterations mapping within the L2-enhancer element and show that two of these observed lesions eliminate the ability of the enhancer element to direct gene expression in the L2 primordium. The L2 enhancer can be subdivided into distinct activation and repression domains. The activation domain mediates the combined action of the general wing activator Scalloped and a putative locally provided factor, the activity of which is abrogated by a single nucleotide alteration in the ri53j mutant. We also find that misexpression of genes in L2 that are normally expressed in veins other than L2 results in abnormal L2 development. These experiments provide a mechanistic basis for understanding how kni and knrl link AP patterning to morphogenesis of the L2 vein by orchestrating the expression of a selective subset of vein-promoting genes in the L2 primordium.

Key words: knirps, radius incompletus, L2 vein, wing, Drosophila melanogaster, Patterning, Morphogenesis

INTRODUCTION

One of the important remaining questions in developmental biology is to understand how positional information is linked to the genesis of specific morphological structures in different locations of the organism. The Drosophila wing is a system that is particularly well suited for studying the relationship between patterning and morphogenesis. For example, mechanisms for establishing positional information along the anterior-posterior (AP) axis have been analyzed in detail (reviewed by Lawrence and Struhl, 1996; Strigini and Cohen, 1999; Klein, 2001) and morphological structures such as the five major longitudinal veins (L1-L5) form at invariant positions along the AP axis of the adult wing (reviewed by García-Bellido and de Celis, 1992; Bier, 2000). As described below, the five wing veins can be distinguished from one another by several criteria including: expression of specific combinations of genes during development; whether they are located primarily on the dorsal or ventral surfaces of the wing (odd versus even numbered veins respectively); and by the types or absence of sensory organs that form along them (e.g. sensory organs form on the L1 and L3 veins, but not on the L2, L4 or L5 veins). An interesting question then, is how vein-specific as well as more general vein developmental programs are initiated at various locations in response to different positional information.

Wing vein development in Drosophila can be subdivided into two temporally distinct stages: initiation and differentiation. Vein initiation begins during the mid-third larval instar (Waddington, 1940; García-Bellido, 1977; García-Bellido and de Celis, 1992; Sturtevant et al., 1993; Sturtevant and Bier, 1995; Bier, 2000) when the wing imaginal disc is a monolayer of cells. The wing blade proper derives from an oval region of the wing disc known as the wing pouch, while the remainder of the disc generates elements of the wing hinge and thoracic body wall. Vein differentiation, the second phase of vein development, occurs during metamorphosis as the wing disc buds out (or everts), folding along the future wing margin. Ultimately, this eversion leads to the apposition of the dorsal and ventral surfaces of the wing during pupal development, creating the bilayer of cells comprising the mature wing blade.

Genes involved in initiating wing vein development (vein genes) are expressed during the third larval instar in narrow stripes, corresponding to vein primordia, or in broader ‘pro-
vein’ stripes, consisting of cells that are competent to become vein cells (Biels et al., 1998). Some vein genes are expressed in all vein primordia, while others are expressed in subsets of veins or in single veins. For example rhomboid (rho), which encodes an integral membrane protein (Bier et al., 1990; Sturtevant et al., 1996), is expressed in all vein primordia and promotes vein formation throughout wing development by locally activating the Egfr signaling pathway (Sturtevant et al., 1993; Noll et al., 1994; Bier, 1998a; Bier, 1998b; Guichard et al., 1999). Caupolican (caup) and the neighboring gene araucan (ara) encode related homeobox genes that promote expression of other vein genes such as rho in odd numbered veins. Promeatal genes such as achaete (ac) and scute (sc) promote neural development in the L1 and L3 primordium (Gomez-Skarmata et al., 1996). Delta (Dl) encodes a ligand for the Notch (N) receptor, which mediates lateral inhibitory interactions among cells in vein-competent domains during pupal development (Shellenbarger and Mohler, 1978; Kooh et al., 1993; Parody and Muskavitch, 1993). Delta is also expressed earlier during larval stages of wing development in all longitudinal veins except L2, and is likely to play a role in limiting vein thickness at this stage as well, since loss of Notch function during larval development leads to greatly broadened expression of the vein marker rho (Sturtevant and Bier, 1995). kni and knrl, which encode related zinc finger transcription factors in the steroid hormone superfamily (Nauber et al., 1988; Oro et al., 1988; Rothe et al., 1989), are expressed in a single stripe corresponding to the L2 primordium beginning in the mid-third larval instar, and are required to initiate L2 development (Lunde et al., 1998). kni also functions as a gap gene in early embryonic development (Nüsslein-Volhard and Wieschaus, 1980; Nauber et al., 1988).

The L2 stripe of kni/knrl-expressing cells forms along the anterior border of a broad domain of cells expressing high levels of the related and functionally overlapping spalt-major (salm) (Kühnlein et al., 1994) and spalt-related (salr) (Barrio et al., 1996) zinc finger transcription factors. A variety of evidence indicates that central domain cells expressing the patterning genes salm and salr (together referred to as sal) induce their anterior neighbors, which express very low levels of sal, to become the L2 primordium (Sturtevant et al., 1997; Lunde et al., 1998). For example, in wings containing salr-mutant clones, ectopic branches of L2 are induced that track along and inside the salr- clone borders, mimicking the normal situation in which an L2 vein forms just outside the domain of high-level sal-expressing cells (Sturtevant et al., 1997). This ability of sal-expressing cells to induce their anterior low-level sal-expressing neighbors to initiate L2 development requires the activity of the kni locus (Lunde et al., 1998). The induction of knilknrl expression in the L2 primordium therefore provides an excellent system for studying the transition from spatial patterning to tissue morphogenesis.

Once activated along the anterior sal border, kni and knrl organize development of the L2 vein, in part by activating expression of the key vein-promoting gene rho and by suppressing expression of the intervein gene blistered (bs) (Montagne et al., 1996; Lunde et al., 1998). The kni locus is highly selective in regulating downstream gene expression in the L2 primordium as revealed by the observation that several genes expressed in other veins, such as caup and ara, ac and sc, and Delta, are excluded from the L2 primordium. Thus, the kni locus links patterning to vein-specific morphogenesis by functioning downstream of sal and upstream of genes involved in vein versus intervein development.

The role of the kni locus in L2 formation has been clarified by analysis of likely regulatory alleles of the kni locus, previously known as radius incompletus (ri) (Aradjárv and Hannah-Alava, 1969; Lunde et al., 1998). Flies with this mutation lack large sections of the L2 vein. kni53 mutants are homozygous viable, in contrast to kni null mutants, which die as embryos with a gap gene phenotype (Nüsslein-Volhard and Wieschaus, 1980; Nauber et al., 1988). In support of kni53 mutations being wing-specific regulatory alleles of the kni/knrl locus, expression of kni and knrl in the L2 primordium is absent in kni51 mutants, and the L2 vein-loss phenotype can be partially rescued by ubiquitous expression of kni in the wing (Lunde et al., 1998).

The findings summarized above suggest that kni and knrl organize the L2 vein developmental program by orchestrating expression of genes that execute distinct subsets of functions required for proper L2 development. Several important unanswered questions remain, including: what function(s) are disrupted in kni51 and other existing kni mutants?; do these mutations eliminate the function of an L2-specific cis-regulatory element in the kni locus?; and finally, with respect to the definition of L2 versus other veins, is it important to exclude expression of genes expressed in veins other than the L2 primordium?

In this study we report the identification of an enhancer element upstream of the kni coding region that selectively directs gene expression in the L2 primordium in third instar larval wing discs. We show that three separate ri alleles have defects mapping within a minimal 1.4 kb L2 enhancer element. We demonstrate that two of these mutations eliminate activity of the L2 enhancer, kni51, which contains a 252 bp deletion, and kni53, which harbors a single base-pair substitution. We find that truncation of the minimal L2 enhancer to a 0.69 kb fragment leads to ectopic reporter gene expression in the extreme anterior and posterior regions of the wing, indicating that repression contributes to restricting activation of the L2 enhancer. In addition, we show that the general wing promoting transcription factor Scalloped (Sd) binds with high affinity to several sites in the L2 enhancer and that sd is required for kni expression in the wing disc. We have also employed the L2 enhancer element as a tool to drive expression of various UAS transgenes in the L2 primordium. We find that the loss of the L2 vein in ri mutants can be rescued by L2-specific expression of either the kni or knrl genes, or the downstream target gene rho. In addition, we find that misexpression of genes in the L2 primordium that are normally expressed in veins other than L2 results in abnormal L2 development. These results provide a framework for understanding how positional information is converted into morphogenesis of the L2 wing vein by ‘vein organizing genes’ such as kni and knrl.

**MATERIALS AND METHODS**

**Fly stocks**

The weak kni51[M3] allele isolated by J. Díaz-Benjumea was kindly
provided by Antonio García-Bellido (Universidad Autónoma de Madrid); Ruth Lehmann (Skirball Institute, New York) provided the strong viable Df(3L)knirps(1) allele and the Dr(3L)knirps(CS) stock (Lehmann, 1985); Peter Portin (University of Turku) provided the knirps(21) allele; Yuh Nung Jan provided the UAS-scute stock (Chien et al., 1996); Juan Modolell (Universidad Autonoma De Madrid) provided the UAS-era and UAS-caup stocks; Amanda Simcox (Ohio State University) provided the UAS-vein stock (Simcox et al., 1996); Joachim Urban (Universitat Mainz) provided the UAS-eg stock (Dittrich et al., 1997); Ken Irvine (Waksman Institute) provided the pBSI and T7 promoters containing the side of the vector most proximal to the knirps coding region. The constructs were subcloned into the lacZ transformation vector pC4PLZ. Subfragments of the 4.8 kb EcoRI fragment (fragment E in Fig. 1) that drive expression in the L2 primordium were then subcloned into pC4PLZ to define a minimal L2 enhancer element. To assay fragments of E, pBS-E was digested; the proximal most EcoRI-SalI (ES, 2.0 kb), EcoRI-XhoI (EX, 1.4 kb), and EcoRI-HindII (EC, 0.69 kb) fragments were isolated and re-inserted into pBS. The 4.8 kb fragment E was also subcloned into the pc4PG4 expression vector, in which the lacZ gene in pC4PLZ has been replaced by GAL4 (Emery, 1996), and was used to drive expression of various UAS transgenes in the L2 primordium.

Mapping of kni and ri breakpoints
Restriction fragments isolated from a lambda phage walk (Nauber et al., 1988) covering over 50 kb of the kni upstream region, delimited by the Df(3L)knirps(1) deletion, were used as probes to determine the locations of potential chromosomal abnormalities such as deletions or rearrangements in ri mutants on Southern blots (Southern, 1975). Several different restriction enzymes were used to scan each region to distinguish single nucleotide polymorphisms from larger scale abnormalities such as those present in the kni(1) and kni(1M) mutants.

Isolation of kni(1) genomic fragments and construction of the E[r]-lacZ vectors
Primers AA and RK were used to amplify a region surrounding the proximal EcoRI-BglII (1.197 kb) fragment of E from knirps(1), knirps(2), knirps(1M), and knirps(53) genomic DNA (AA=GAAGAAATCTCCGAGA ATTCC, the 5’ end is in F, the 3’ end contains the EcoRI site; RK=CCCCAATTGCACAACTTTGGTGGG, the 5’ end is at 1.231 kb in E. Note that TGGGG was added to produce a Kn1 site at the distal end of the resulting fragment). PCR fragments were purified for sequencing using the QIAquick PCR Purification kit. The blunt ended kni(1) fragment was cloned into pCR-BluntII-TOPO (TOPO) and oriented so that the Norl site within TOPO and the BglII site within the fragment (N, B) are on opposite sides. The resulting TOPO-N.B construct and pBS-E were digested with Norl and BglII, fragments isolated and ligated to form pBS-ER[1]. The ER[1] insert was sequenced to confirm that it differed from the wild-type sequence by only the 252 bp deletion. Knpl and Norl were used to remove ER[1], and it was cloned into the corresponding sites of pC4PLZ to form ER[1]-lacZ. Similarly, primers ECO-ri and Xba-ri were used to PCR amplify the EcoRI-XhoI fragment of E (termed EX) from knirps(53) genomic DNA (ECO-ri=GAATTCCAGGGAGGAGCGTC; Xba-ri=TCTAGATGGGCTGCCTGGCA). The resulting 1.4 kb product was cloned into the TOPO vector. The EX(r735) fragment was digested with EcoRI and XbaI and subcloned into the corresponding sites of pC4PLZ to form ER(r735)-lacZ. A single subclone was sequenced to verify that only the single nucleotide change (C596A) had been incorporated.

Generation and analysis of sd(1) clones
Generation of reduction-of-function sd(1) clones and immunohistochemical analysis were performed as described previously (Guss et al., 2001).

Analysis of sd binding sites in the L2 enhancer
Identification and analysis of sd binding sites was performed as described by Guss et al., 2001. Sequences of the upper strand of oligonucleotides used as probes for gel mobility shift assays and as PCR primers to introduce mutations into the sd binding sites of the kni(0.69) element (fragment EC in Fig. 1F) are listed below in the 5’ to 3’ orientation. Altered bases are shown in lowercase in the mutant version, and the corresponding bases are underlined in the native sequence as follows:

- kni(1) wild type: TTCCCCCTCTTTACATTGTTGCGCAGATGTTTCCATCTTGCCCA
- kni(1) mutant: TTCCCCCTCTTTCTATGTTGCGCAGATGTTTCTGCTTTAATTTGCCTTTAATT
- kni(570) wild type: TTGCGGACACAGGAGACACGGACACGGAGAGAGTTTTGCTTTGTTTGCTTTAATT
- kni(570) mutant: TTGCGGACAGGAGAGACACC ATGACGAgGTTTGTGCTTTAATT
- kni(640) wild type: TTGCGGTTGCGCAGACAGAATGTTGTTGAGAGTTTGGAAATGTTGAGG
- kni(640) mutant: TTGCTGTTGCGACTGAAAGAATGTTGTTGAGGATTG

Reporter constructs with three mutated Sd binding sites were made by cloning PCR-generated fragments of fragment EC into the Hsp lacZ-CaSpeR plasmid (Nelson and Laughton, 1993). Four independent EC-3sdmut-lacZ transfectants were recovered and tested for lacZ expression.

Mounting fly wings
Wings from adult flies were dissected in isopropanol and mounted in 100% Canada Balsam mounting medium (Aldrich #28,292-8) as described previously (Roberts, 1986).

In situ hybridization to whole-mount larval wing discs
In situ hybridization using digoxigenin-labeled antisense RNA probes (O’Neill and Bier, 1994) was performed alone or in combination with anti β-galactosidase (Promega) labeling as described previously (Sturtevant et al., 1993).

RESULTS
An L2 enhancer element lies upstream of the knirps coding region
In a previous study, we presented genetic evidence that the kni(1) mutation, as well as an approximately 50 kb deletion of kni upstream sequences (Df(3L)knirps(1X)), disrupt the function of a wing-specific regulatory element in the kni locus that is
Fig. 1. Map of knirps locus and ri alleles. (A) A wild-type adult male wing. Longitudinal wing veins (L1-L5), and margin (M) are indicated. (B) A knirps[1] homozygous adult male wing, with an incomplete L2 vein. Note that this phenotype is somewhat milder than that of Df(3L)knirps[XT2] mutants (C). (C) A Df(3L)knirps[XT2] homozygous adult male wing. Note the virtual absence of veins (L1-L5), and margin (M) are indicated. (B) A knirps[1] homozygous adult male wing. (E) Diagram of region 77E1 in the left arm of the third chromosome showing kni and knrl transcripts, the regions deleted in Df(3L)knirps[XT2] and Df(3L)knirps[FC82] as well as lacZ test constructs (EcoRI fragments) E (red), F (green), S (orange), R (brown), and Q (pink). The fragment labeled abd-lacZ (white box) has been shown to contain an embryonic enhancer (yellow box) driving expression in abdominal segments (Pankratz et al., 1992). This fragment does not drive gene expression in the wing primordium. Genomic DNA fragments between E and S were not tested in lacZ fusions. The 4.8 kb fragment E drives reporter gene expression in L2. abd (yellow box), embryonic abdominal enhancer (Pankratz et al., 1992); CG13252, a predicted protein-coding transcript that is expressed ubiquitously in both wild-type and knirps[53j] wing discs (data not shown). The knirps transcript, which comprises 23 kb of genomic DNA (Rothe et al., 1992), is not drawn to scale. The 5′ end of the knirps gene is at –74.8 kb on this map. (F) Expanded map of 4.8 kb fragment E, showing the 1.4 kb minimal L2 driver (black), 252 bp knirps[1] deletion (dark blue), C to A base substitution at 0.596 kb in E in knirps[53j] (light blue), and the region of insertion(s) or rearrangements in knirps[FC82] (turquoise), from 0.998 to 0.686, and from 1.99 to 3.44 kb. (G) lacZ transgenic constructs made to assay expression driven by a region containing the knirps[1] deficiency substituted into E (EΔri[1]), and successively smaller 3′ subfragments of E: EX, 1.4 kb; and EC, 0.69 kb.
expression (Fig. 2D). Notably, the weaker posterior E-lacZ stripe forms immediately adjacent to the posterior border of the salm domain (Fig. 2D).

In order to delimit a minimal L2 enhancer element, we tested the ability of 5' truncated derivatives of the 4.8 kb fragment E (Fig. 1G) to drive reporter gene expression in larval wing imaginal discs. We observed that subfragments of 2.0 kb (EcoRI-SalI, data not shown) and 1.4 kb (the EcoRI-XhoI fragment EX, Fig. 1G) drive expression of lacZ (Fig. 2E) in patterns nearly indistinguishable from that of the 4.8 kb E-lacZ construct (Fig. 2B).

Further truncation generating a 0.69 kb EcoRI-HindII fragment (EC, Fig. 1G), however, results in high levels of ectopic lacZ expression in broad anterior and posterior domains (Fig. 2F). This observation indicates that regulatory element(s) required to repress gene expression in the extreme anterior and posterior domains of the wing primordium reside between the distal 0.69 kb and 1.4 kb of fragment EX (repression domain, Fig. 3B), and that sequences sufficient for activation are contained within the proximal 0.69 kb fragment EC (activation domain, Fig. 3A). As discussed below, we have identified sequences necessary for L2 activity in the activation domain as well as potential repressor binding sites in the proposed repression domain (Fig. 3A, B, Fig. 7).

ri mutants have lesions in the L2 enhancer that disrupt its function

As a complement to screening genomic fragments upstream of the kni locus for the ability to drive gene expression in the L2 primordium using lacZ promoter fusion constructs, we scanned the approximately 50 kb region deleted in the Df(3L)kni[XT2] allele for detectable aberrations in five putative independently isolated ri alleles. Using a series of probes spanning that complete genomic region (Fig. 1E), we found that a single EcoRI fragment (the same fragment E that drives expression in the L2 primordium) contains aberrations in the kni[1], kni[92f], kni[M4] and kni[M3] mutants. For each of these alleles, mutations map within the minimal 1.4 kb L2 enhancer element (see Fig. 1F). Although no large-scale lesions were detected by Southern blot analysis within fragment E of the kni[53j] mutant, subsequent sequence analysis identified a single base pair alteration within the minimal L2 enhancer element EX (see below). The kni[53j] allele is also associated with a small deletion (approx. 50 bp) in fragment R.

Further molecular analysis of the various ri alleles revealed that the putative independently derived kni[1], kni[92f], and kni[M4] alleles all contain the same 252 bp deletion. As this deletion is not flanked by duplicated sequences that could promote frequent identical recombination events, it may be that the kni[92f] and kni[M4] alleles are actually re-isolates of the original kni[1] mutation. Consistent with these three alleles having a common origin, they also share a restriction enzyme polymorphism (i.e. loss of a HindIII site) in fragment Q (Fig. 1E) that is not shared by the other ri mutants or our white control stock. To test whether the 252 bp deletion within the minimal L2 enhancer element is responsible for the loss of kni and kni1 gene expression in kni[1] mutants, we made a kni[1], mutated E-lacZ construct. We amplified genomic DNA containing the kni[1] mutation and substituted it for the corresponding part of the original E-lacZ construct to generate EΔri1-lacZ (Fig. 1G) and transformed this construct into flies. We examined lacZ expression in third instar larval wing discs of EΔri1-lacZ flies and found that they failed to express lacZ in the L2 primordium or anywhere else in the wing pouch (Fig. 2G), indicating that the 252 bp deletion in kni[1] mutants eliminates the activity of the L2 enhancer element.

Since Southern blot analysis did not reveal any obvious lesions in fragment E of the kni[53j] allele, we considered the possibility that this allele might have a subtler lesion in the L2 enhancer region. Accordingly, we PCR amplified and

Fig. 2. Expression of wild-type and mutant L2 enhancer constructs. (A) kni expression in a wild-type mid-third instar larval wing disc. The L2 primordium (L2) and margin (M) are indicated. (B) lacZ expression driven by the E-lacZ construct in a mid-third instar larval wing disc. Note the lower levels of lacZ expression in a diffuse stripe in the posterior region of the wing pouch (arrow). (C) E-lacZ expression relative to endogenous kni mRNA expression (blue) and anti-β-galactosidase protein (brown). Note the high degree of coincidence of these two expression patterns. (D) E-lacZ expression relative to salm mRNA expression in a mid-third instar larval wing disc double-stained for kni mRNA expression (blue) and anti-β-galactosidase protein (brown) and salm expression (blue). Note the abutting and mutually exclusive expression of these two genes. (E) EX-lacZ expression driven by fragment EX (1.4 kb 3′ subfragment of E; see Fig. 1G) in a mid-third instar larval wing disc. (F) EC-lacZ expression driven by fragment EC (0.69 kb 3′ subfragment of E; see Fig. 1G) in a mid-third instar larval wing disc. Note the broad anterior and posterior domains of ectopic lacZ expression relative to that driven by the E-lacZ and EX-lacZ constructs. (G) E-Δri1-lacZ expression driven by the fragment E-Δri1, which is deleted for the same 252 bp segment that is missing in the ri[1] allele, in a mid-third instar larval wing disc. (H) EΔri1-lacZ expression relative to endogenous kni mRNA expression (blue) and anti-β-galactosidase protein (brown) and salm expression (blue). Note the higher degree of coincidence of these two expression patterns.
sequenced the 1.4 kb fragment (EX, Fig. 1G) corresponding to
the minimal L2 enhancer from \textit{kni}\textsuperscript{ri[53j]} . We found only a single
nucleotide difference between the sequence of this mutant
allele and the wild-type fragment EX (C596A, Fig. 3A), which
lies within the same 252 bp region deleted in \textit{kni}\textsuperscript{ri[1]} . Although
it has been observed that single nucleotide mutations can
eliminate endogenous enhancer function (Shimell et al., 1994),
such cases are sufficiently rare that it was important, as in the

\textbf{Fig. 3.} The L2-enhancer element is activated by Sd.
(A) Sequence of the \textit{EcoRI-HindII} fragment (EC) of E,
which contains sites necessary for activation of the minimal L2
erenhancer (0 to 0.691 kb of fragment E). (B) Sequence of the
\textit{HindII-XhoI} fragment, which contains sequences
required to repress ectopic activity of the L2 enhancer element (0.692 to 1.361 kb of
fragment EX). Key: The deletion in the \textit{kni}\textsuperscript{ri[1]} mutant is indicated by blue text and the
nucleotide mutated in the \textit{kni}\textsuperscript{ri[53j]} mutant (C to A at 596)
highlighted in turquoise. Sd binding sites in fragment EC
(underlined in brown) were determined empirically by
footprinting and gel shifts. A tandem doublet of binding sites begins at 271
[TACATTGTCGCATAGTT], while the sites beginning at 463
[TGATACTAT] (opposite strand), 523 [AAAAATGTGC],
570 [GAAATGCGT], and 640 [ACTATTTCT] (opposite
strand) are single sites. These experimentally determined sites
define a consensus
[(A/T)(A/G)NA T(G/T)TNT], which matches well with the
consensus [WRVVATKRY] derived for Sd binding to other
wing enhancers that require \textit{vestigial} and \textit{sd} function such as
\textit{bs=DSRF} (Halder et al., 1998),
\textit{cut}, \textit{sal} and the \textit{vg} quadrant element (Guss et al., 2001).
Other predicted DNA binding
sites are indicated based on
matches to known consensus
sequences. Engrailed (En)
[TATAA – yellow type]: (Ades
and Sauer, 1994); Spalt-related
(Salr) [TTA TGa/tAa/cT – pink
type]: (Barrio et al., 1996);
Brinker (Brk) [ctGCCAg/c – green type]: (Rushlow et al., 2001; Zhang et al., 2001). No predicted DNA binding sites were identified in
fragment EX for Mad (Kim et al., 1997), Ci (Kinzler and Vogelstein, 1990), or Kni (Small et al., 1996). (C-F) Reporter gene expression driven
by the 4.8 kb element E is dependent upon \textit{sd} function. (C) A mitotic clone homozygous for the hypomorphic \textit{sd}\textsuperscript{58} allele located in the wing
pouch is marked by the absence of the MYC epitope tag and is outlined in red. (D) Expression of the \textit{E-lacZ} reporter gene is eliminated or
reduced by the reduction of \textit{sd} function, except in clones along the wing margin, where it is unaffected (data not shown). The yellow arrowhead
indicates the position of the \textit{sd}– clone. (E) The position of cells is marked by the nuclear dye TOPRO. (F) Merged image of panels A-C. (G) Gel
mobility shift assays of oligonucleotide probes spanning the tandem binding sites at 271, and the single sites at 570 and 640, with the Sd TEA
domain (left panels of each pair). Mutations introduced at these sites (right panels of each pair), reduce Sd binding. F, free probe; 1, probe with
one Sd TEA domain bound; 2, probe with two Sd TEA domains bound. (H) A wing disc from one of the transformant lines in which the 271
doublet, and 570, 640 single Sd sites were mutated in the context of fragment EC.
case of kni[ri1], to demonstrate whether this point mutation was responsible for the loss of enhancer function. We used the EX kni[ri53] PCR fragment to make a lacZ construct, confirmed the sequence of the mutant construct, generated four independent transformants, and tested these flies for lacZ expression in third instar wing discs. We found that EX(rf53)-lacZ mutant wing discs fail to express lacZ in the L2 primordium (Fig. 2H), strongly suggesting that this single base pair mutation is responsible for the observed L2 vein loss phenotype observed in kni[ri53] flies. One notable difference between the EX(rf53)-lacZ and EAr1-lacZ mutant wing discs is that in the point mutant construct (ri53), lacZ expression is lost selectively in the L2 primordium and in the weaker posterior stripe (note the normal levels and pattern of expression in extreme anterior and posterior regions of the disc, Fig. 2H), while in the deletion mutant construct (EAr1), reporter gene expression is eliminated throughout the wing disc (Fig. 2G).

As noted above, the kni[ri53] mutant is also associated with a deletion of ≈50 bp in fragment R, which lies approximately 15 kb 5′ to fragment E within predicted intron sequences of a putative transcription unit (see kni locus map, Fig. 1E). As the ubiquitous expression of this transcription unit is not affected in kni[ri53] mutants (K. L., unpublished observations) and fusion of fragment R with lacZ does not result in gene expression in the L2 primordium, we have no evidence to suggest that this aberration has any relevance to the L2 vein loss phenotype of kni[ri53] mutants.

Analysis of the kni[RI3] allele indicates that this mutation involves an insertion and possibly rearrangements within fragment E. One breakpoint of the kni[RI3] allele falls within the 1.4 kb EX minimal L2 enhancer element (Fig. 1F). Because this is a relatively weak ri allele and is associated with a complex lesion, we did not characterize the nature of this rearrangement further.

The wing selector protein Scalloped binds to the L2 enhancer and is required for its activity

The 4.8 kb L2 enhancer fragment E and truncated derivatives (fragments EX and EC) drive reporter gene expression specifically in the wing pouch. Recent work has shown that gene expression in the wing primordium is controlled by Sd, which functions with Vestigial (Vg) to define wing identity (Kim et al., 1996; Kim et al., 1997; Halder et al., 1998; Simmonds et al., 1998; Guss et al., 2001; Halder and Carroll, 2001). We tested whether Sd binds to the kni L2 enhancer. We searched for specific Sd DNA binding sites in the 0.69 kb EC activation domain using DNAse I footprinting and gel shift analysis (Fig. 3G and data not shown) and identified five sites bound by the Sd TEA domain, which conform well to the known Sd consensus binding site and consist of a tandem doublet of Sd binding sites and four single binding sites (Fig. 3A). The four single Sd sites are removed by the 252 bp deletion in the kni[ri1] allele, however, none of them covers the kni[ri53] point mutation. To determine whether Sd plays a direct role in activating the L2 enhancer, we mutated a subset of these Sd binding sites in the context of the EC-lacZ construct, transformed these mutated constructs into flies and stained for lacZ expression in third instar wing discs. We found that mutation of the doublet at 271 in combination with the two single sites at 570 and 640 resulted in a complete loss of lacZ expression in the wing disc (Fig. 3H). These results indicate that Sd is required for activation of kni expression in the wing disc.

kni[ri1] mutants can be rescued by kni, knrl or the downstream target gene rho

Having shown that the minimal L2 enhancer is mutated in several independently derived ri alleles (kni[ri1], kni[RI3], and kni[ri53]), we wished to know whether driving expression of either the kni or knrl genes with this element could rescue the ri vein-loss phenotype. We addressed this question using the conditional GAL4/UAS expression system of Brand and Perrimon (Brand and Perrimon, 1993). We created transgenic flies that carry fragment E driving GAL4 expression (L2-
GAL4) and used this driver to activate expression of UAS-kni or UAS-knr1 transgenes in the L2 primordium of kni\textsuperscript{[1]} mutants. As expected, GAL4 RNA is expressed in the L2 primordium of L2-GAL4 wing discs (Fig. 4A). We placed this L2-GAL4 driver and the UAS-kni and UAS-knr1 transgenes into the kni\textsuperscript{[1]} mutant background and generated flies of the genotype L2-GAL4>UAS-kni; kni\textsuperscript{[1]}/kni\textsuperscript{[1]} (Fig. 4B) and L2-GAL4>UAS-knr1; kni\textsuperscript{[1]}/kni\textsuperscript{[1]} (Fig. 4C). These flies have fully restored L2 veins that resemble wild-type L2 veins in that the bulk of the vein is formed on the ventral surface of the wing.

Since rho is known to play a critical role in activating Egfr signaling in all vein primordia, we also determined whether expression of this downstream effector of the kni locus could bypass the requirement for kni in kni\textsuperscript{[1]} mutants. We found that L2 formation is indeed rescued in L2-GAL4>UAS-rho; kni\textsuperscript{[1]}/kni\textsuperscript{[1]} flies (Fig. 4D). As in the case of rescue by kni or knr1, the rescued L2 vein forms primarily on the ventral surface of the wing.

**Misexpression of genes expressed in veins other than L2 alters L2 development**

As mentioned above (see Introduction), several genes that are important for vein development are expressed in veins other than L2. For example, the vein- and sensory organ-promoting gene ara is expressed in the odd numbered veins (L1, L3, and L5), the proneural genes ac and sc are expressed in L1 and L3, and the Notch ligand Delta is expressed in L1 and L3-L5, but not in L2. We were interested to know whether it is necessary to exclude expression of these genes from the L2 primordium for normal L2 development. To address this question, we misexpressed UAS-transgene copies of these genes in the L2 primordium with the L2-GAL4 driver and examined the L2 vein in adult wings. In each case, we observed defects in L2 development. Misexpression of the lateral inhibitory signal Delta in L2-GAL4>UAS-Dl flies results in modest truncation of the L2 vein in females (Fig. 5A) and almost entirely eliminates the L2 vein in sibling males (Fig. 5B), which are the consistently more severely affected sex. The near elimination of L2 development in severely affected Dl-misexpressing males is accompanied by a loss of rho expression in the L2 primordium of third instar larval wing discs (Fig. 5D, compare with wild-type rho expression in Fig. 5C). Misexpression of the proneural gene sc in the L2 primordium of L2-GAL4>UAS-sc flies results in L2 veins covered with ectopic bristles (Fig. 5E). The great majority of these ectopic bristles are strictly confined to the L2 primordium, consistent with the double label experiments (Fig. 2C) indicating that the L2-enhancer element drives gene expression precisely in the L2 primordium. In addition, ectopic bristles form sporadically in a broad posterior domain of the wing, which derives from a region of the wing disc in which the L2 enhancer element is also expressed in a weak diffuse pattern (Fig. 2B,D). Finally, misexpression of the ara gene in L2-GAL4>UAS-ara flies causes a reproducible thinning of the L2 vein (Fig. 5F). Collectively, these results underscore the importance of excluding expression of non-L2 vein genes from the L2 primordium.

The L2-GAL4 driver can be used as a tool to dissect gene function and range of action

As discussed above, the L2-GAL4 driver activates UAS transgene expression precisely in the L2 primordium. The ability to drive highly localized expression of genes in a non-essential tissue with L2-GAL4 suggests that this driver could be used as an effective tool to dissect the function and range of action of various genes. For example, since
the eagle (eg) gene encodes a steroid hormone receptor closely related to Kni and Knrl (Rothe et al., 1989) we wondered whether this gene could substitute for kni or knrl in rescuing kni[1] mutants. eg is involved in neuroblast specification during embryogenesis (Higashijima et al., 1996; Dittrich et al., 1997; Lundell and Hirsh, 1998), but is not expressed in the wing pouch (data not shown) and is not known to play a role in development of the wing proper. We found that, as in L2-GAL4>UAS-kni; kni[1]/kni[1] individuals, L2 formation is rescued in L2-GAL4>UAS-eg; kni[1]/kni[1] flies, however, this restored ‘L2’ vein is decorated with a line of ectopic sensory bristles (Fig. 6A). As the same ectopic bristles are observed in L2-GAL4>UAS-eg individuals (data not shown), this phenotype can be attributed to misexpressing eg in the L2 primordium. By employing the L2 expression system it should now be possible to map the domain in Eg that is responsible for inducing ectopic bristles using chimeric Eg/Kni receptors.

The L2 expression system should also be useful in distinguishing cell-autonomous from non cell-autonomous gene activity. As a test of this idea we compared the phenotypes resulting from driving expression of an activated form of the Egfr (ltop) in the L2 primordium versus expression of the secreted Egfr-like ligands Vein (Schnepf et al., 1996) and sSpitz (Schweitzer et al., 1995; Schnepf et al., 1998). Consistent with ltop acting in a cell autonomous fashion to promote vein versus intervein development, expression of this gene in the L2 primordium of L2-GAL4>UAS-ltop wings (Fig. 6B) had no effect on the development of the L2 vein or neighboring intervein cells. In contrast, when secreted Egf ligands were expressed in a similar fashion in L2-GAL4>UAS-vn wings (Fig. 6C) or in L2-GAL4>UAS-sspi wings (Fig. 6D), we observed ectopic veins that formed 2-3 cell diameters away from the L2 vein. Similarly, when we co-expressed rho and Star in the L2 primordium (e.g. in L2-GAL4>UAS-rho; UAS-Star wings; Fig. 6E), which also generates a potent secreted Egfr promoting activity (Guichard et al., 1999), we observed ectopic veins that were displaced from the endogenous L2 vein by a few cells. The ability of secreted ligands, but not the ltop construct, to induce ectopic vein formation at a distance cannot be attributed simply to the latter being a weaker activator of Egfr signaling since UAS-ltop is considerably more effective at generating ectopic veins than UAS-vn when other wing-GAL4 drivers are used (e.g. MS1096-GAL4 or CY2-GAL4, data not shown).

We also observed a non cell-autonomous activity of the Wingless (Wg) ligand in L2-GAL4>UAS-wg wings (Fig. 6F), which had ectopic veins displaced from the endogenous L2 as well as ectopic marginal bristles near the intersection of L2 with the margin. These ectopic marginal bristles always formed on the appropriate surface of the wing (Fig. 6F, insert), suggesting that this phenotype may result from the inappropriate activation of the wing margin genetic program.

**DISCUSSION**

An important step in understanding the link between patterning and morphogenesis is to identify key cis-regulatory elements that lie at the interface of these sequential processes. Formation of the L2 vein provides a potential paradigm for connecting patterning initiated by a morphogen (e.g. a centrally positioned...
BMP activity gradient) to the activation of a vein differentiation program in a narrow stripe of cells in the wing imaginal disc (e.g. controlled by kni/knrI). In this study we have identified a cis-acting regulatory element that drives expression of the kni locus in the L2 primordium. We found that three distinct mutations causing L2 vein truncations alter this regulatory element and that in at least two of these cases the mutations disrupt the function of the enhancer. Dissection of this enhancer element indicates that a locally provided activating signal acts in conjunction with broadly distributed activating (sd dependent) and repressive systems to limit activation of the L2 enhancer to a sharp stripe of cells in the wing imaginal disc. We also found that excluding expression of non L2 vein genes from the L2 primordium is essential for normal L2 development.

**ri mutants are L2-enhancer specific regulatory alleles of the kni locus**

The results described in this study demonstrate definitively that **ri** mutations are regulatory alleles of the **kni** locus disrupting the function of a cis-regulatory enhancer element that drives gene expression in the L2 primordium of wing imaginal discs. A crucial line of evidence supporting this conclusion is that mutant versions of the L2 enhancer incorporating either the 252 bp deletion present in **kni** or the single base pair substitution present in **kni** elimate the ability of this element to direct gene expression in the L2 primordium. In addition, it is possible to completely rescue the vein-loss phenotype of **kni** by expressing either the UAS-kni or UAS-knrI transgenes with an L2-GAL4 driver. Consistent with activation of rho being one of the key effectors of kni/knrI function, it is also possible to rescue the L2 vein-loss phenotype of **kni** by expressing a UAS-rho transgene in L2, although rescue is less complete and penetrant than that observed with UAS-kni or UAS-knrI.

The isolation of the L2 enhancer also addresses an unresolved question regarding the basis for the failure of *Df(3L)kniFC82* to complement (*Lunde et al., 1998*). As these two deletions have endpoints that break within the same 1.7 kb EcoRI fragment (indicated by the dashed vertical lines in Fig. 1E), one explanation for the failure of complementation could be that this 1.7 kb fragment contains the L2 enhancer. The alternative explanation for the **ri** phenotype of *Df(3L)kni** is that transvection (*Lewis, 1954; Geyer et al., 1990; Pirrotta, 1999,* which normally occurs between regulatory and coding region alleles of the **kni** locus (*Lunde et al., 1998,* is interrupted by the large divergent deletions that have little if any overlap. Since the 4.8 EcoRI fragment containing the L2 enhancer maps nearly 10 kb upstream of the 1.7 kb EcoRI fragment, and a lacZ fusion construct (abd-lacZ, Fig. 1E) containing the 1.7 kb EcoRI fragment does not drive any gene expression in the wing disc (*Lunde et al., 1998,* the latter hypothesis that *Df(3L)kni** and *Df(3L)kniFC82* are unable to engage in effective transvection is the most likely explanation for the failure of these two mutations to complement. **Global activation, regional repression and localized induction restrict L2-enhancer activity to a narrow stripe of cells**

The results of these and previous studies of L2 vein initiation lead to a model in which localized vein inductive signaling acts against a background of regional repression and global wing-specific activation (Fig. 7A). Previous genetic experiments have suggested a model in which sal-expressing cells produce a short-range L2 inducing signal (X) to which sal-expressing cells themselves cannot respond (*Sturtevant et al., 1997; Lunde et al., 1998*). According to this ‘for export only’ signaling model, the signal X diffuses into adjacent anterior cells and activates expression of the kni/knrI genes in the L2 primordium, in much the same fashion as Hh, expressed from the refractory posterior compartment, activates expression of target genes such as dpp or ptc in the anterior compartment (reviewed by *Bier, 2000*). Based on the analysis of the L2 enhancer element described in this study, the 252 bp region deleted in **ri** mutants may contain response element(s) to this putative factor X. It is worth noting, however, that lacZ expression is lost in all cells of the wing disc (posterior and circumferential cells as well as the L2 primordium) when these sequences are deleted from the 4.8 kb fragment. This observation suggests that sequences mediating more general activation (e.g. Sd binding sites, see below) may also be contained within this 252 bp region. The sequence surrounding the single nucleotide alteration in **ri** mutants (CS96A), however, is a particularly intriguing candidate for mediating the L2-specific activation of **kni** since introducing this mutation in the context of the minimal 1.4 kb enhancer leads to selective loss of lacZ expression only in the stripe of cells adjacent to the sal domain.

The hypothetical transcription factor X’ (Fig. 7B) that binds to the region surrounding the **ri** point mutation and mediates the inductive signal X presumably collaborates with the more generally required wing selector Sd (*Halder et al., 1998; Guss et al., 2001,* since mutation of four of the Sd binding sites (the doublet and two single sites) in the L2 activation domain completely eliminates enhancer activity in the wing disc. Clonal analysis with a hypomorphic sd allele also indicates that **sd** is required for high-level expression of the full 4.8 kb L2 enhancer element in the wing disc. It is notable that the reduction in lacZ expression in these clones is not as dramatic as the complete loss of L2 activity observed when Sd binding sites in the activation domain are mutated. There are several possible explanations for this discrepancy. Firstly, the **sd** mutation used in these experiments is a hypomorphic allele and therefore has residual activity. Unfortunately, stronger **sd** alleles produce even smaller viable clones in the wing disc and thus were not used. Secondly, as only small clones can be generated, they must typically have been produced with only two or three intervening cycles of cell division. Consequently, the **sd** cells may still contain functional levels of wild type Sd (protein perdurance). Another possibility is that other activators can partially substitute for Sd, at least in certain regions of the wing. Based on the absence of L2 activity when Sd binding sites are mutated and the reduction in L2 activity in **sd** hypomorphic clones, we conclude that Sd plays an important role as an activator of the L2 enhancer. These results support the view that Sd functions as a general transcriptional activator of genes expressed in the wing field.

Repression also plays a key role in restricting L2 enhancer expression to a narrow stripe of wing disc cells. It has been shown previously that salm and salr, which are expressed
strongly in the central region of the wing, repress expression of \textit{kni} and \textit{knrl} (Lunde et al., 1998), although low levels of \textit{sal} may also be required to activate \textit{kni} expression (de Celis and Barrio, 2000). In the current study we also find evidence for repression of L2-enhancer activity in peripheral wing disc cells abutting those expressing high levels of \textit{sal}. Truncation of the minimal 1.4 kb (fragment EX) L2 enhancer element results in reporter gene expression expanding to fill the anterior and posterior regions of the wing pouch in a pattern complementary to that of \textit{sal}. The region deleted from the EX fragment contains several consensus binding sites for Brinker (Fig. 3B, Fig. 7B) (Rushlow et al., 2001; Zhang et al., 2001), which may mediate this repression. The pattern of \textit{brinker} (\textit{brk}) expression in the wing pouch (Campbell and Tomlinson, 1999; Jazwinska et al., 1999) is very similar to that of \textit{lacZ} expression driven by the 0.69 kb fragment EC. One way to integrate the action of the localized inductive signal X$\rightarrow$X$'$ pathway with that of abutting central and peripheral repressive factors is to propose that the signal-dependent activator X$'$ can overcome the repressive action of the peripheral inhibitor but not repression by Salm/Salr (see legend to Fig. 7). One feature common to several prominent signaling pathways is that activation of the pathway converts a resting repressor into a transcriptional activator (Barolo and Posakony, 2002). In the \textit{kni} L2 enhancer, activation of the hypothetical signal X pathway may relieve repression by a heterologous repressor since the putative activator (i.e. X$'$) and repressor (e.g. Brk?) sequences in the L2 enhancer are separable. One example of a signaling pathway that functions by relieving inhibition by a heterologous repressor is the recent report of Egfr signaling inactivating repression by Suppressor of Hairless (Su(H)) (Tsuda et al., 2002). In addition to central and peripheral repression in the wing disc, there may also be a repressor in posterior compartment cells (e.g. En, Fig. 7A,B) to prevent activation of the L2 enhancer in cells posterior to the \textit{sal} expression domain. Perhaps the 4.8 kb L2 enhancer element lacks some sites for this putative repressor since \textit{E-lacZ} drives significantly higher levels of gene expression in the posterior
stripe than that observed for endogenous \textit{kni} or \textit{knrl} expression.

**Expression of non-L2 vein genes must be excluded from the L2 primordium**

All longitudinal veins share several morphological characteristics such as being composed of densely packed cells on both the dorsal and ventral surfaces of the wing that secrete a thickened cuticle. The primordia of all longitudinal veins also express the \textit{rhomboid} gene, which is required for activating the Egfr pathway in vein but not in intervein cells. In addition to these shared properties, each vein can be distinguished by expression of other vein genes (Biehs et al., 1998). For example, vein L2-specific characteristics include: expression of \textit{kni} and \textit{knrl}, lack of Delta expression, lack of \textit{cauplara} expression, and lack of \textit{aclsc} expression. Given that all veins are ultimately quite similar morphologically, it is relevant to ask whether the differences in gene expression patterns observed in different veins are important.

In this study, we examined the necessity of excluding expression of non-L2 vein genes in the L2 primordium by forcing expression of genes such as \textit{Dl}, \textit{ara}, \textit{ac} and \textit{sc} in L2 and asking whether this manipulation had any impact on L2 development. These experiments strongly suggest that exclusion of non-L2 vein genes from the L2 primordium is indeed important since misexpression of each of these genes resulted in abnormal L2 development. The phenotypes resulting from misexpressing non-L2 vein genes in the L2 primordium can largely be reconciled with the normal functions of these genes. For example, forced expression of \textit{Dl} leads to loss of L2, consistent with suppression of vein formation by Notch signaling. The ectopic bristles that form strictly along the L2 vein in wings misexpressing \textit{ac} or \textit{sc} are also consistent with the neural promoting function of proneural genes. It is less clear why misexpression of the \textit{ara} gene causes thinning of the L2 primordium, since this gene normally activates expression of the vein-promoting gene \textit{rho} in odd numbered veins and \textit{ac} and \textit{sc} in the L3 primordium. Perhaps expression of a gene normally involved in development of the odd numbered dorsal veins is somehow incompatible with development of the ventral L2 vein.

**The L2 expression system provides a localized assay for gene function in the wing**

The sharp stripe of gene expression driven by L2-GAL4 can also be used as a rapid assay to test the function or range of action of various genes in the wing. For example, in the case of the Egfr pathway, it is possible to distinguish components exerting cell-autonomous versus non cell-autonomous functions. In line with the fact that activation of the Egfr pathway in the wing leads to the formation of veins, L2-GAL4-driven expression of the secreted ligand \textit{sSpi} generates ectopic veins in the neighborhood of L2 while expression of the equally potent constitutively active \textit{top} form of the EGF receptor does not result in a non-autonomous phenotype. The L2 expression system may also be used to compare the functions of related genes such as the nuclear receptors Kni, Knrl, and Eg. Although these three transcription factors share nearly identical DNA binding domains and can all rescue the vein-loss phenotype of \textit{ri} mutants, they differ in that misexpression of \textit{eg} in the L2 primordium induces the formation of ectopic bristles along L2. This distinct activity of \textit{eg} may relate to its normal embryonic function in directing cell fate choices in the CNS. Using the L2 expression system as an assay, it should be straightforward to map the domain in \textit{eg} that is responsible for its neural inducing capacity by constructing chimeric molecules composed of different domains of \textit{Eg} and \textit{Kni}. Finally, the observation that L2-driven expression of \textit{Dl} leads to a highly penetrant loss of L2 in males and a consistently weaker phenotype in females provides the basis for a modifier screen to identify mutations that either suppress the phenotype in males or enhance the phenotype in females. Some of the modifier loci identified in such a screen, which are not specifically involved in Notch signaling, may encode components of the hypothesized factor $X\rightarrow X'$ pathway.

We thank Orna Cook and Margaret Roark for critical comments on the manuscript, and Dan Ang for help with preparing figures. This work was supported by NIH grant NIH R01 GM60585 and NSF grant NSF IBN-0094634. K. A. G. acknowledges the support of Sean B. Carroll, in whose lab the studies on the role of \textit{ad} were performed. This work was funded by NIH 1F32HD08326 to K. A. G., and the Howard Hughes Medical Institute, of which Sean B. Carroll is an Investigator.

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