The bromodomain protein LIN-49 and trithorax-related protein LIN-59 affect development and gene expression in Caenorhabditis elegans

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SUMMARY

We have molecularly characterized the lin-49 and lin-59 genes in C. elegans, and found their products are related to Drosophila trithorax group (trx-G) proteins and other proteins implicated in chromatin remodelling. LIN-49 is structurally most similar to the human bromodomain protein BR140, and LIN-59 is most similar to the Drosophila trx-G protein ASH1. In C. elegans, lin-49 and lin-59 are required for the normal development of the mating structures of the adult male tail, for the normal morphology and function of hindgut (rectum) cells in both males and hermaphrodites and for the maintenance of structural integrity in the hindgut and egg-laying system in adults. Expression of the Hox genes egl-5 and mab-5 is reduced in lin-49 and lin-59 mutants, suggesting lin-49 and lin-59 regulate HOM-C gene expression in C. elegans as the trx-G genes do in Drosophila. lin-49 and lin-59 transgenes are expressed widely throughout C. elegans animals. Thus, in contrast to the C. elegans Polycomb group (Pc-G)-related genes mes-2 and mes-6 that function primarily in the germline, we propose lin-49 and lin-59 function in somatic development similar to the Drosophila trx-G genes.

Key words: HOM-C gene expression, Trithorax group (trx-G) genes, Hindgut development, Caenorhabditis elegans

INTRODUCTION

Correct regulation of gene expression during development requires a variety of different proteins, ranging from cell-type specific transcription factors to the basal transcription machinery. Since DNA is tightly packaged in vivo, one important class of proteins involved in transcription is proteins that affect the accessibility of DNA. Such proteins are proposed to regulate chromatin structure and thereby either allow for or interfere with the expression of genes. Recent work has focused on a collection of multiprotein complexes that can affect gene expression by directly modifying nucleosomes and altering chromatin structure (reviewed by Kingston et al., 1996; Pollard and Peterson, 1998). Although a large number of these complexes have been described, how their function correlates with gene regulation during development in vivo largely remains to be characterized.

Of the proteins that participate in the maintenance of transcriptional states in animal development, the best characterized have been those encoded by the Polycomb group (Pc-G) and trithorax group (trx-G) genes in Drosophila. These genes were originally identified for their role in affecting expression of genes in the Bithorax and Antennapedia complexes that specify regional identity along the anterior/posterior axis (HOM-C genes; reviewed by Kennison, 1995). Genetically, Pc-G and trx-G genes represent two distinct classes, but the genes in each class encode a variety of different types of proteins. Nevertheless, many Pc-G and trx-G proteins include sequence motifs that suggest they associate with chromatin and participate in transcriptional regulation. In vivo, Pc-G genes act as transcriptional repressors, and trx-G genes act as transcriptional activators. Both molecular and genetic results point to a model in which Pc-G and trx-G proteins influence gene expression by affecting chromatin structure and thus contribute to establishing and maintaining specific transcriptional states (discussed by Papoulas et al., 1998).

Molecular homologues of Pc-G and trx-G genes are found in all animals. Recent work in C. elegans, however, suggests these genes may function differently in the development of nematodes compared to flies. Two genes (called mes-2 and mes-6) are the orthologues of the Pc-G genes E(z) and esc (Holdeman et al., 1998; Korf et al., 1998). In C. elegans, mutations in these genes confer a maternal-effect sterile phenotype (Capowski et al., 1991). mes-2 and mes-6 are required for transcriptional repression (Kelly and Fire, 1998), but their expression and function is mostly limited to the germline. Thus, in C. elegans these Pc-G homologues act differently from Pc-G genes in Drosophila, as they don’t appear to play a critical role in the developmental regulation of HOM-C gene expression, or in other aspects of somatic development. In addition, the sequenced C. elegans genome includes homologues to only these two of the nine molecularly characterized Pc-G genes (C. elegans sequencing consortium, 1998). Because of these differences between C. elegans and
Drosophila Pc-G genes, an important question is whether the developmental functions of the trx-G genes is likewise different between the two species. Homologues of some trx-G genes are present in the C. elegans genome (Table 1). However, the function of none of these C. elegans trx-G-related genes has previously been reported.

Because the mating structures of the C. elegans adult male tail derive from precursor cells in the posterior body region, alleles of the posterior HOM-C genes egl-5 and mab-5 have been recovered in genetic screens for mutations that disrupt male tail development (Hodgkin, 1983; Kenyon, 1986; Chow and Emmons, 1994; Chamberlin et al., 1999). In such a screen, we identified two new genes (lin-49 and lin-59) with mutant phenotypes similar to each other. We have molecularly characterized these two genes, and found that they both encode products with similarity to trx-G gene products and other proteins that affect gene expression. We provide phenotypic and gene expression data suggesting that these genes affect the expression of the C. elegans HOM-C genes egl-5 and mab-5 like trx-G genes do in Drosophila. Thus lin-49 and lin-59 are important in somatic development and share some developmental functions with the Drosophila trx-G genes.

MATERIALS AND METHODS

Strains

Nematodes were cultured according to standard techniques (Sulston and Hodgkin, 1988). Mutations and strains used are described by Hodgkin (1997) and as indicated.

Linkage group (LG) I: lin-59(sa489)
LG III: unc-119(e2498)
LG IV: lin-22(n372), lin-49(s1198), lin-49(sy238), lin-49(sa470), unc-22(s7), unc-31(e169), d(f18), nT1
LG V: him-5(e1490), muIs3 (mab-5::lacZ; Cowing and Kenyon, 1992), muIs13 (egl-5::lacZ; Wang et al., 1993)

Extrachromosomal arrays: saEx422, saEx423 (R107.1::gfp), saEx491, (lin-49::gfp). saEx425, saEx426 (lin-59::gfp)

Germline transformation and rescue of lin-49 and lin-59 mutant phenotypes

lin-49 and lin-59 were mapped to genetic intervals on LG IV and I, respectively (Chamberlin et al., 1999). We tested cosmid that maps within each interval for transgenic rescue of mutations. DNA was microinjected into the mitotic germline of hermaphrodites according to standard methods (Sambrook et al., 1989). In such a screen, we identified two new genes (lin-49 and lin-59) with mutant phenotypes similar to each other. We have molecularly characterized these two genes, and found that they both encode products with similarity to trx-G gene products and other proteins that affect gene expression. We provide phenotypic and gene expression data suggesting that these genes affect the expression of the C. elegans HOM-C genes egl-5 and mab-5 like trx-G genes do in Drosophila. Thus lin-49 and lin-59 are important in somatic development and share some developmental functions with the Drosophila trx-G genes.

<table>
<thead>
<tr>
<th>Table 1. Trx-G homologues in C. elegans</th>
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<tr>
<td><strong>Drosophila</strong></td>
</tr>
<tr>
<td>Orthologues</td>
</tr>
<tr>
<td>BRM</td>
</tr>
<tr>
<td>TRR</td>
</tr>
<tr>
<td>ASH2</td>
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<tr>
<td>Similar*</td>
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</tr>
<tr>
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<tr>
<td>ASH1</td>
</tr>
<tr>
<td>Homeodomain‡</td>
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<tr>
<td>BA/HD L</td>
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</table>

No C. elegans homologues were found for Trx-G proteins TRL/GAGA, KIS and MOR.

*Although these proteins have modest blast scores they share similarity within several domains across the protein.

‡A second protein, C26E6.9/10, has a higher blast score (167), but T1D8.1 has more similarity over the full extent of the protein.

These proteins share similarity only within the homeodomain, but the Trx-G protein is the closest Drosophila homologue for the C. elegans protein.

Several cDNA clones for both lin-49 and lin-59 were identified by Yuji Kohara and the C. elegans cDNA sequencing project. They provided three clones for lin-49 (yk3323c10, yk42a12, yk33c1) and three for lin-59 (yk40b5, yk32b5, yk18a4). Using restriction enzyme digests, we verified that the clones in each set were similar. We then sequenced the longest for each gene to identify splice junctions and 3’ and 5’ ends (see DNA sequence analysis, below). For lin-49, the clone yk33c1 included a 3687 bp cDNA of the entire predicted coding region and the 3’ untranslated region, but lacked the full 5’ untranslated region. We have submitted the sequence of this cDNA to the GenBank database (accession no. AF163018). For lin-59, the clone yk32b5 included a cDNA of the 3’ untranslated region and the coding regions of exons 5-8. To complete the 5’ end, we used random primed first strand cDNA as template for the polymerase chain reaction (RT-PCR) using lin-59-specific primers and a primer to the SL1 splice leader as in Chamberlin et al. (1997). The resultant composite cDNA sequence of 4696 bp was submitted to the GenBank database (accession no. AF163019).

Construction of lin-49::gfp, lin-59::gfp and R107.1::gfp transgenes

We made a green fluorescent protein (GFP) reporter construct for lin-49 expression (pTJ1241) by cloning a 3.7 kb Pst/HindIII promoter fragment from pTJ1033 into pPD95.67 (all pPD vectors were received from Andy Fire). We made a GFP reporter construct for the sodium dicarboxylate cotransporter-related gene R107.1 (pTJ996) by cutting the 7.6 kb Sal/XbaI insert from pUL#AL32 (Lynch et al., 1995) and cloning it into pPD95.70. We made a GFP reporter construct for the sodium dicarboxylate cotransporter-related gene R107.1 (pTJ996) by cutting the 7.6 kb Sal/XbaI insert from pUL#AL32 (Lynch et al., 1995) and cloning it into pPD95.70. Transgenes were produced by microinjection of plasmid DNA into animals, as described above. For lin-49::gfp, 45 ng/µl pTJ1241 was co-injected with 30 ng/µl pDpMM016 (unc-119(+)) plasmid; Maduro and Pilgrim, 1995) and 100 ng/µl pBluescript KS+ into unc-119(e2498); him-5(e1490) hermaphrodites. For lin-59::gfp, 100 ng/µl pTJ1068 was coinjected with 30 ng/µl pDpMM016. For R107.1::gfp, 200 ng/µl pTJ996 was co-injected with 15 ng/µl pDpMM016.

DNA sequence analysis

PCR fragments and cDNA clones were sequenced by the University of Washington Biochemistry sequencing facility using an ABI PRISM sequencer (Perkin-Elmer). We amplified genomic DNA from mutant animals according to the single worm PCR method of Barstead et al. (1991). PCR fragments covering all exons of each gene were
sequenced. The DNA from at least two independent reactions was used as template to sequence both strands in regions containing the mutations. We used BLAST 2.0 (Altschul et al., 1997; http://www.ncbi.nlm.nih.gov/BLAST/) to identify and evaluate the molecular homologues of trx-G proteins, LIN-49 and LIN-59, and ClustalW 1.7 (Thompson et al., 1994b; http://dot.imgen.bcm.tmc.edu:9331/) and Boxshade 3.21 (http://www.isrec.isb-sib.ch:8080/software/BOX_form.html) to align and display the sequence motifs presented in Figs 1 and 2.

**Phenotypic analysis of mutants**

Young adult males were observed using Nomarski optics at 1000x magnification. The morphology of their tail structures was compared to wild type, and the extent of lateral alae differentiation was scored according to the method of Kenyon (1986), using the landmarks of Wrischnik and Kenyon (1997). Differentiation of ectopic spicule socket cells in adult lin-48 mutant males was scored after killing the B or B.a cell in L1 or L2 larval stage males, as previously described (Chamberlin et al., 1999). The male animals were also scored for distorted intestinal lumen (Con). Early L4 hermaphrodites were observed using Nomarski optics at 1000x to evaluate the extent of vulval development according to the criteria of Sternberg and Horvitz (1986). Viability of adult hermaphrodites was scored by placing one to five L4 hermaphrodites on fresh plates, and then scoring their morphology and viability each day. Animals that did not move when prodded were scored as dead. For all experiments, both the scored animals and their mothers were raised at the indicated temperature (15°C or 20°C).

**Analysis of transgene expression in mutants**

lin-49(sa470) and lin-59(sa489) are all temperature sensitive, with mutant phenotypes enhanced at 25°C (Chamberlin et al., 1999). However, homozygous mutant strains cannot be maintained at high temperatures. To test transgene expression at 25°C, parents were shifted from 20°C and their progeny were analyzed for expression 2 days later. The animals raised at 25°C for 2 days are still viable (they still move, eat, etc.), but they are enhanced for mutant defects. Animals of both sexes and all larval stages were counted. The strain JT9876 unc-119(e2498); him-5(e1490); saEx423 was used as the parent strain and as the wild-type control for R107.1::gfp expression. R107.1::gfp expression initiates in late embryogenesis and persists through all larval stages to adulthood. saEx423 was crossed into strains and maintained on the basis of its ability to rescue unc-119 mutations. To score expression, non-Unc larvae were anesthetized on pads of 5% agar in water containing 5 mM sodium azide, and scored for sex, larval stage and GFP expression at 1000x magnification. Transgenic animals were verified by confirming expression of R107.1::gfp in non-hindgut cells prior to scoring. This method may over-represent the level of expression in mutant animals, as transgenic animals without any detectable expression would not be counted. Cells were scored positive for expression if any GFP fluorescence was detected above background.

Larvae of all stages exhibit expression of egl-5::lacZ and mab-5::lacZ transgenes, although the expression patterns change with development. For our tests, animals were scored for presence and level of expression but not for which cells express. To detect β-galactosidase activity, mixed stage animals were stained according to the method of Fire (1986). Staining was stopped by rinsing animals and wild-type animals. To detect the effects of lin-49 and lin-59 mutations, animals were exposed long enough for >50% of wild-type animals to develop staining, but not to saturation. Table 1A,B (egl-5::lacZ-bearing animals in Table 6 were stained for 15 minutes at 37°C.

**RESULTS**

We recovered alleles of lin-49 and lin-59 in a genetic screen for mutations that disrupt *C. elegans* male tail development (Chamberlin et al., 1999). Mutations in these two genes confer similar developmental defects and are pleiotropic, and genetic analysis indicated that lin-49 and lin-59 are essential genes. We initiated a molecular analysis of these genes to better understand their developmental functions.

**lin-49 encodes a bromodomain protein similar to human BR140**

We genetically mapped lin-49 to linkage group IV between mes-6 and fem-3, which provided a left-most and right-most boundary for lin-49 on the physical map. We identified one cosmid in this region (F42A9) that rescued lin-49(s1198) in 4 of 4 heritable lines. A 9.2 kb subclone of F42A9 that includes only one predicted gene, F42A9.2, also rescued lin-49(s1198) in 2 of 2 heritable lines. This transgenic rescue, in combination with the sequence of lin-49 mutations (below), identified F42A9.2 as lin-49.

To determine the structure of lin-49 mRNAs, we obtained and completed the sequence of a corresponding cDNA clone identified by Y. Kohara (Fig. 1). The sequence can be translated to produce a 1042 amino acid protein which contains a bromodomain and a region with regularly spaced cysteines and histidines (the cysteine rich region). Each of these domains is found in several proteins, including two Drosophila trx-G proteins (Fig. 1B,C). However, besides LIN-49, the only protein reported to contain both domains is human BR140. Since a function for BR140 has not been reported, LIN-49 provides the first functional characterization for this class of bromodomain proteins.

The bromodomain is found in many chromatin-associated proteins, including most known histone acetyltransferase (HAT)-associated transcriptional co-activators (Jeannotte et al., 1997). In vitro studies indicate the domain participates in protein-protein interactions (e.g., Barlev et al., 1998). In particular, the bromodomain of the HAT co-activator P/CAF can interact specifically with acetylated lysine, suggesting the bromodomain may confer on proteins the capacity of acetylation-dependent protein-protein interactions (Dhalluin et al., 1999). However, where it has been tested, deletion of the domain does not disrupt protein function in vivo, indicating other regions of bromodomain-containing proteins can compensate in its absence (Candau et al., 1997; Elfing et al., 1998).

The cysteine rich region of LIN-49 includes seventeen cysteines and four histidines that are regularly spaced and invariant between LIN-49 and other proteins that contain this sequence motif (Fig. 1B). The cysteine rich region includes one embedded PHD finger (C4–H–C3). The PHD finger is a recognized sequence motif found in some chromatin-associated proteins, but its function is not known (Aasland et al., 1995). The extended similarity throughout the cysteine rich region identifies LIN-49 and other proteins that contain this motif as a distinct subgroup of PHD-containing proteins. In addition, the functional importance of the cysteine rich region is suggested by the observation that two lin-49 mutations are missense mutations within this motif (below).

We sequenced DNA from lin-49 mutant animals (Fig. 1A,B). The lethal allele, s1198, is a tgG → tgA transition that
Fig. 1. The lin-49 gene and its product. The complete sequence of a lin-49 cDNA was submitted to GenBank (accession no. AF163018). A. lin-49 consists of ten exons and encodes a protein with a bromodomain (striped) and a cysteine rich region (gray) that includes a PHD finger (black). One nonsense and two missense mutations localize to the cysteine rich region. B. Alignment of the cysteine rich region from LIN-49 and other proteins. The PHD finger is boxed. The amino acids affected in mutants are indicated with *. Six representative proteins with the cysteine rich region are shown in addition to LIN-49. At least ten additional protein sequences with this domain are in GenBank. C. Alignment of the bromodomain from LIN-49 and other proteins. C.e., Caenorhabditis elegans; H.s., Homo sapiens; S.c., Saccharomyces cerevisiae; S.p., Schizosaccharomyces pombe.

results in a Trp278 → Stop. This mutation should result in a truncated protein lacking half the cysteine rich region and the bromodomain. This mutation is consistent with genetic results, which indicate sl198 is a strong reduction of function or potential null allele of lin-49. The viable alleles, sa470 and sy238, each result in an amino acid substitution at an invariant cysteine in the cysteine rich region. sa470 is a Tgc → Agc transversion that results in a Cys325 → Ser substitution. sy238 is a tGt → tAt transition that results in a Cys330 → Tyr substitution. The phenotype of animals bearing sa470 or sy238
in trans to deletions that remove lin-49, or in trans to the lethal allele s1198, is enhanced compared to homozygous mutants (Chamberlin et al., 1999). Thus we believe these mutations reduce, but do not eliminate lin-49 activity.

**lin-59 encodes a SET domain protein similar to the product from the Drosophila trx-G gene ash1**

We genetically mapped lin-59 to linkage group I between fog-1 and unc-11, which provided a left-most and right-most boundary for lin-59 on the physical map. We identified two cosmids in the region (F21A9 and T12F5) that each rescued lin-59(s1198) (4 of 4 and 1 of 1 heritable lines, respectively). The approx. 20 kb overlap region between the two cosmids included three predicted genes. We created a deletion derivative of T12F5 that included only one of these predicted genes (T12F5.4) and showed that this cosmid rescued lin-59.
59(sa489) (4 of 4 heritable lines). Based on this transgenic rescue and the sequence of the lin-59(sa489) mutation, we conclude T12F5.4 is lin-59.

To determine the structure of lin-59 mRNAs, we completed the sequence of a cDNA clone identified by Y. Kohara. This cDNA corresponds to the 3’ portion of lin-59, and includes the 3’ untranslated region and exons 5-8. To complete the cDNA, we used RT-PCR to amplify and sequence the 5’ end. This produced a full length cDNA sequence of 4696 bp (Fig. 2). The sequence can be translated to produce a 1312 amino acid protein. LIN-59 is most similar to the product of the Drosophila trx-G gene, ashl (Tripoulas et al., 1996). LIN-59 and ASH1 both contain a central SET domain, and share similarity in the carboxyl terminus which includes one PHD finger. The SET domain is found in several classes of proteins, including some products of Pc-G and trx-G genes, and it has been implicated in mediating protein-protein interactions (Cui et al., 1998; Rozenblatt-Rosen et al., 1998). Although both LIN-49 and LIN-59 contain a PHD finger, the carboxyl terminal region shared by LIN-59 and ASH1 is not otherwise similar to the cysteine rich region found in LIN-49-related proteins (discussed above).

We sequenced DNA from lin-59(sa489) mutant animals. sa489 is a tGg to tAg transition that results in a premature amber stop codon. This mutation would result in a truncated protein missing the 122 carboxyl terminal amino acids, including part of the region conserved between LIN-59 and ASH1. The phenotype of animals bearing sa489 in trans to a deletion that removes lin-59 is enhanced compared to homozygous mutants (Chamberlin et al., 1999). Thus, we believe sa489 is not a null allele.

**lin-49::gfp and lin-59::gfp transgenes are expressed broadly in somatic tissues**

Human BR140 and Drosophila ashl are both expressed broadly throughout the organism (Thompson et al., 1994a; Tripoulas et al., 1994). To investigate the expression of lin-49 and lin-59 we constructed reporters consisting of each promoter driving expression of GFP, and expressed them in transgenic animals. We found that embryonic expression of lin-59::gfp is first detected in mid-blastula stage. Subsequently it is expressed in most cells of the animal, throughout development and into adulthood (Fig. 3). lin-49::gfp transgenes are expressed at lower levels, but with a similar pattern. This transgene expression is consistent with lin-49 and lin-59 being expressed throughout the animal.

**Mutations in lin-49 and lin-59 confer some phenotypes found in HOM-C mutants**

lin-49 and lin-59 mutants share a range of phenotypes, and the viable alleles of lin-49 and lin-59 are temperature sensitive for embryonic and larval lethality (Chamberlin et al., 1999). To further characterize the mutant phenotypes and the temperature sensitivity, we scored both male and hermaphrodite animals for morphological defects. In particular, we focused on male alae production and fan morphogenesis and hermaphrodite vulval development since these tissues are known to be affected by mutations in HOM-C genes.

Mutations in C. elegans HOM-C genes interact with mutations in lin-22, a C. elegans hairy homologue (Kenyon, 1986; Wrischnik and Kenyon, 1997). lin-22 affects the anterior/posterior identity of a set of lateral epidermal cells called V cells. Normally, the more anterior V cells (V1-V4) produce seam cell progeny that generate alae (lateral cuticular ridges). In male animals, the more posterior V cells (V5-V6) produce progeny that differentiate as structures in the adult male tail called rays. In males mutant for the HOM-C gene mab-5, V5 and V6 behave like their more anterior neighbors, and produce alae rather than rays. In contrast, in lin-22 males V1-V4 behave like their posterior neighbor V5, and produce rays at the expense of alae. The lin-22 mutant phenotype results, at least in part, from ectopic MAB-5 expression. Consequently, mab-5; lin-22 double mutants produce more alae than lin-22 single mutants. Mutations in the HOM-C genes egl-5 and lin-39 can also modify the lin-22 mutant phenotype (Wrischnik and Kenyon, 1997).

To investigate the role of lin-49 and lin-59 in anterior/posterior patterning, we asked whether mutations in these genes affect alae production and interact with lin-22 (Fig. 4). We found that lin-49 and lin-59 mutants have defects in anterior/posterior patterning of V cells. At both 15°C and 20°C, mutant males produce occasional ectopic rays, and alae that fail to extend to the normal posterior position and that include gaps. In addition, the alae can extend further anterior than normal. Thus, lin-49 and lin-59 affect anterior/posterior patterning, but they are distinct from mab-5 and lin-22. To test for genetic interactions, we constructed double mutants with lin-22. At 15°C lin-22 lin-49 double mutant males generally produced more alae than lin-22 single mutants (the lin-22 lin-49 double mutants are sick and difficult to grow at 20°C). This indicates lin-49 genetically interacts with lin-22 in a manner similar to mab-5. lin-59; lin-22 doubles do not produce

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**Fig. 3. lin-59::gfp expression. (A) Nomarski photomicrograph of an L1 transgene-containing animal. (B) Fluorescence image, showing widespread expression of lin-59::gfp. Scale bar, 20 μm.**
appreciably more alae than lin-22 single mutants, although they still produce alae that extend further anterior than normal. Since the lin-59 allele is not null, we can not distinguish between the possibility that lin-59 is different from lin-49 in its interaction with lin-22 and the possibility that the lin-59 mutation is not strong enough to show an effect.

In addition to the occasional ectopic rays that result from defects in patterning V cells, lin-49 and lin-59 mutant males have defects affecting the fan and bursa (Table 2). These defects range from animals with simple ray fusions to more general defects in morphogenesis (Table 3; Fig. 5E,F). Chow and Emmons (1994) have shown that reduction of egl-5 and mab-5 activity can result in a transformation of the identity of ray 4 to that of ray 3. Consequently, these rays fuse together to form a single ray. We have observed similar ray fusions in lin-49 and lin-59 mutants. For example, of lin-49(sa470) males raised at 15°C with a fused or missing ray phenotype, 10 of 22 (45%) had ray 3 and ray 4 fused together. lin-49(sy238) and lin-59(sa489) mutants showed similar types of ray fusion defects. In addition to ray fusions, ray 5 and ray 6 were sometimes misplaced or even transposed (Fig. 5E and data not shown), suggesting failure of the normal migration or morphogenesis of these cells.

To further investigate the role of lin-49 and lin-59 in the development of structures that require normal HOM-C gene activity, we characterized the development of the hermaphrodite-specific vulval structures in the midbody region. Normally, the hermaphrodite vulva forms from the progeny of three ventrally located epidermal cells (P5.p, P6.p, and P7.p). In hermaphrodites mutant for the HOM-C gene lin-39, these cells behave like their anterior and posterior counterparts and fuse with the syncytial hypodermis (hyp 7) rather than divide to form the vulva (Clark et al., 1993).
resulting animals are vulvaless, and incapable of laying eggs. In general, hermaphrodites of \textit{lin-49} and \textit{lin-59} genotypes are capable of laying eggs (Table 4 legend), indicating they are not vulvaless. We scored the extent of vulval differentiation in \textit{lin-49(sy238)} mutants, and found that P7.p, or sometimes P5.p, failed to divide in 12 of 43 (28%) \textit{lin-49(sy238)} mutant hermaphrodites raised at 20°C, suggesting some similarity to \textit{lin-39} mutants. However, five of five \textit{lin-49(sy238)/sDf18} animals that survived to L4 stage and 16 of 16 \textit{lin-49(sa470)} homozygotes had normal vulval development. We have not ruled out the possibility that the observed vulval defect results from another mutation in the \textit{lin-49(sy238)} background. Thus, \textit{lin-49} and \textit{lin-59} mutant hermaphrodites have only minor, if any, defects in vulval development.

\textbf{Mutations in \textit{lin-49} and \textit{lin-59} affect development of male spicule and hook structures}

In \textit{lin-49} and \textit{lin-59} males the spicules can be misformed, and in some animals they are greatly reduced in size or apparently missing, suggesting a defect in spicule development or differentiation (Table 2; Fig. 5B,C). Normally, all of the cells of the spicules derive from the precursor cell B (Sulston et al., 1980). Males with mutations in a gene called \textit{lin-48} make ectopic spicule cells that derive from another precursor, U.

\textbf{Table 3. Severity of fan defects is temperature sensitive in \textit{lin-49} and \textit{lin-59} mutants}

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Temp. (°C)</th>
<th>Fused/missing rays</th>
<th>Swollen/def. morphogenesis</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>\textit{lin-49(sa470)}</td>
<td>15</td>
<td>85</td>
<td>15</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>46</td>
<td>54</td>
<td>48</td>
</tr>
<tr>
<td>\textit{lin-49(sy238)}</td>
<td>15</td>
<td>83</td>
<td>17</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>8</td>
<td>92</td>
<td>50</td>
</tr>
<tr>
<td>\textit{lin-59(sa489)}</td>
<td>15</td>
<td>77</td>
<td>23</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>40</td>
<td>60</td>
<td>42</td>
</tr>
</tbody>
</table>

All males with fan defects were classified as having either minor (fused/missing rays) or severe (swollen/def. morphogenesis) fan defects. Numbers represent percentage of total males with fan defects. Animals are the same scored in Table 2.

\textbf{Table 4. Adult \textit{lin-49} and \textit{lin-59} mutant hermaphrodites have reduced viability}

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Temp. (°C)</th>
<th>inviable*</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Wild type</td>
<td>15</td>
<td>2</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>\textit{lin-49(sa470)}</td>
<td>15</td>
<td>9</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>23</td>
<td>43</td>
</tr>
<tr>
<td>\textit{lin-49(sy238)}</td>
<td>15</td>
<td>40</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>41</td>
<td>61</td>
</tr>
<tr>
<td>\textit{lin-59(sa489)}</td>
<td>15</td>
<td>85</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>59</td>
<td>51</td>
</tr>
</tbody>
</table>

All genotypes include \textit{him-5(e1490)}).

Six animals (of the 419 total tested) died because they bagged (the progeny hatched inside the mother and they killed her). These include one wild-type animal at 15°C, two \textit{lin-49(sy238)} animals at 20°C, two \textit{lin-49(sa470)} animals at 20°C and one at 15°C. Three of these \textit{lin-49} mutants were initially egg-laying competent, but bagged after they developed hernia at the vulva.

*Numbers indicate percentage of adult hermaphrodites who died within one generation (3 days at 20°C and 5 days at 15°C). Since metabolism is slowed at lower temperatures, we believe these time points are an appropriate comparison. Percentage inviable after 3 days at 15°C are: \textit{lin-49(sa470)}: 2%; \textit{lin-49(sy238)}: 19%; \textit{lin-59}: 61%.
**Table 5. Reduced production of ectopic spicule cells in lin-59 mutants**

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Cell killed</th>
<th>% with spicule cuticle</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild type*</td>
<td>B1</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>lin-48*</td>
<td>B</td>
<td>67</td>
<td>21</td>
</tr>
<tr>
<td>lin-59; lin-48§</td>
<td>B</td>
<td>9</td>
<td>11</td>
</tr>
</tbody>
</table>

*Data from Chamberlin et al. (1999).
‡B includes animals in which B or B.a was killed (see Materials and Methods).
§Full genotype: lin-59(sa489); lin-48(sy234); him-5(e1490).

To test the genetic relationship between lin-49, lin-59 and lin-48 we conducted double mutants. We found 9% (one of eleven animals) of lin-59; lin-48 double mutants produced ectopic spicule cells, compared to 67% of lin-48 single mutants (Table 5). Since the U cell can develop abnormally in lin-59 mutants (Chamberlin et al., 1999), the lin-59 mutation may block ectopic spicule cell production either by affecting the precursor cell or by affecting differentiation. We found that lin-48; lin-49 double mutants were inviable, so these animals could not be tested for spicule differentiation.

Mutant males also have deformities of the hook (Table 2). The hook can be abnormal or small or completely absent. In some animals it is also displaced anterior to its normal position. Adult males with hook and spicule defects were more likely to have a constipated (Con) phenotype, suggesting these defects compromise the durability of the adult structures. In males it is seen in mutants of both sexes at all stages (Chamberlin et al., 1999).

**Mutations in lin-49 and lin-59 affect the maintenance of organ integrity**

Both male and hermaphrodite lin-49 and lin-59 mutant larvae have cellular and morphological defects within the hindgut (rectum). These defects are associated with defects in structural integrity, and can result in lethality when animals herniate at the anal pore (Chamberlin et al., 1999). In males these defects affect subsequent larval development of the mating structures of the tail (discussed above). In addition to larval defects, we have found that hermaphrodite animals that survive to adulthood are more sickly than wild type, and tend to die young. In particular, adults are prone to defects in structural integrity, and develop hernia at the anal and vulval openings over time. The herniated animals soon die, such that at 20°C after 3 days from 23 to 59% of mutant adult hermaphrodites (depending on genotype) are dead, compared to 0% for wild type (Table 4). This suggests either that lin-49 and lin-59 play a role in adult viability and the maintenance of organ integrity or that earlier developmental defects somehow compromise the durability of the adult structures.

**Table 6. Expression of egl-5::lacZ is moderately reduced in lin-49 and lin-59 mutants**

<table>
<thead>
<tr>
<th>Expt.</th>
<th>Genotype</th>
<th>Expression (%)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wild type</td>
<td>60</td>
<td>136</td>
</tr>
<tr>
<td>1</td>
<td>lin-49</td>
<td>10</td>
<td>107</td>
</tr>
<tr>
<td>2</td>
<td>Wild type</td>
<td>10</td>
<td>87</td>
</tr>
<tr>
<td>2</td>
<td>lin-49</td>
<td>12</td>
<td>125</td>
</tr>
<tr>
<td>1</td>
<td>Wild type</td>
<td>31</td>
<td>111</td>
</tr>
<tr>
<td>1</td>
<td>lin-59</td>
<td>12</td>
<td>124</td>
</tr>
<tr>
<td>2</td>
<td>Wild type</td>
<td>47</td>
<td>137</td>
</tr>
<tr>
<td>2</td>
<td>lin-59</td>
<td>19</td>
<td>133</td>
</tr>
</tbody>
</table>

Animals were tested at 25°C, as described in Materials and Methods. Animals with detectable ß-gal activity were subdivided into ‘weak’ (showing very faint levels) and ‘strong’ (all others). lin-49(sa470) and lin-59(sa489) were used. All genotypes include him-5(e1490).

**Table 7. Expression of a Rep cell marker (R107.1::gfp) is moderately reduced in lin-49 and lin-59 mutants**

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Temp. (°C)</th>
<th>3 2 1 0</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild type</td>
<td>20</td>
<td>47</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>76</td>
<td>16</td>
</tr>
<tr>
<td>lin-49</td>
<td>20</td>
<td>34</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>lin-59</td>
<td>20</td>
<td>28</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>37</td>
<td>29</td>
</tr>
</tbody>
</table>

Animals were tested at 25°C, as described in Materials and Methods. Numbers indicate percent of animals with expression in 3, 2, 1 or 0 of the three Rep cells. lin-49(sa470) and lin-59(sa489) were used. All genotypes include him-5(e1490).

**DISCUSSION**

**LIN-49 and LIN-59 share similarity with proteins implicated in gene expression and chromatin modulation**

We have molecularly characterized the C. elegans genes lin-49 and lin-59. These genes represent the first trx-G-related genes functionally characterized in C. elegans. lin-59 encodes a product similar to that of the Drosophila trx-G gene ash1. LIN-59 and ASH1 share a centrally positioned SET domain and sequence similarity in their carboxyl termini. lin-49 encodes a protein that includes a bromodomain, a domain also found in the trx-G proteins FSH and BRM. LIN-49 is most similar to the mammalian BR140 protein. We have shown that lin-49 is an
The function of lin-49 and lin-59 in C. elegans development

We recovered mutations in lin-49 and lin-59 in a genetic screen for mutations that disrupt male tail development. These mutations result in abnormal development of male-specific tail structures. They also disrupt the morphology, function, and gene expression of hindgut cells in both male and hermaphrodite animals. In addition, these mutations interfere with organ integrity in the hindgut and in the egg-laying system. Consistent with a broad range of functions, lin-49 and lin-59 transgenes are expressed throughout the animal. Nevertheless, in lin-49 and lin-59 mutants we observe the most severe developmental defects in the posterior body region of the animals. Since the viable alleles of lin-49 and lin-59 used in this study are not null, further work will be required to distinguish between the interpretation that these mutations preferentially affect development in the tail region because the tail has a greater requirement for the activity of lin-49 and lin-59 and the interpretation that lin-49 and lin-59 function more broadly, but these specific mutations preferentially disrupt function in the posterior body region.

The molecular identity of LIN-49 and LIN-59 indicates they may function like Drosophila trx-G proteins in activating or maintaining HOM-C gene expression, and our observation that expression of egl-5 and mab-3 transgenes is affected in mutants is consistent with this notion. Genetic analysis also indicates lin-49 and lin-59 affect HOM-C gene activity, as some mutant phenotypes are similar to those seen in egl-5 and mab-5 mutants. Mutants have ray fusions similar to weak mab-5 and egl-5 mutants, and lin-49 acts like mab-5 as a partial suppressor of lin-22. In addition, lin-49 and lin-59 affect the expression or activity of more than HOM-C genes. Mutants have defects in organ integrity that have not been observed in HOM-C mutants. lin-49 and lin-59 single mutant males produce lateral alae with gaps, a phenotype more similar to mab-5; lin-22 double mutants than mab-5 or other HOM-C single mutants (Kenyon, 1986; Wrischnik and Kenyon, 1997). The alae also extend further anterior than normal, a phenotype associated with vab-3 (C. elegans Pax-6) mutants (Chisholm and Horvitz, 1995), but not reported for HOM-C mutants. Expression of additional transgenes (cdh-3 and R107.1) is affected in lin-49 and lin-59 mutants, whereas, where tested, these transgenes are expressed normally in HOM-C mutants (Chamberlin et al., 1999; H. M. C., unpublished). Taken together, these data suggest lin-49 and lin-59 affect the expression of genes in addition to HOM-C genes, as do some of the trx-G genes in Drosophila (Brazuela et al., 1994; Brizuela and Kennison, 1997). Despite the range of affected tissues and genes, the modest and variable effects we observe on individual genes and processes suggest lin-49 and lin-59 play a facilitative rather than essential role in gene expression.

trx-G and Pc-G genes in C. elegans

Our results are consistent with the idea that trx-G and Pc-G-related genes in C. elegans function mechanistically like their Drosophila counterparts. The roles of C. elegans trx-G and Pc-G orthologues in development of the animal, however, are distinct from the roles of the Drosophila genes. In C. elegans, the Pc-G-related genes mes-2 and mes-6 are similar to Drosophila Pc-G genes in acting as transcriptional repressors, but differ in having little role in somatic development (Holdeman et al., 1998; Korf et al., 1998; Kelly and Fire, 1998). Drosophila trx-G genes positively regulate HOM-C gene expression. Our results suggest lin-49 and lin-59 similarly promote HOM-C gene expression, and are important for somatic development. Thus the developmental functions of the C. elegans Pc-G-related genes is altered without a similar change in the function of at least some trx-G-related genes.

The C. elegans genome contains seven Hox genes that are likely orthologues of HOM-C genes. However, they are not as tightly clustered as those in Drosophila and vertebrates are.

REFERENCES


