The lin-41 RBCC Gene Acts in the C. elegans Heterochronic Pathway between the let-7 Regulatory RNA and the LIN-29 Transcription Factor

Frank J. Slack,1,2 Michael Basson,2,3 Zhongchi Liu,3,6 Victor Ambros,1 H. Robert Horvitz,2 and Gary Ruvkun1,4

Department of Genetics
Harvard Medical School and Department of Molecular Biology
Massachusetts General Hospital Boston, Massachusetts 02114
2Howard Hughes Medical Institute and Dartmouth College Hanover, New Hampshire 03755
3Department of Biological Sciences
Harvard Medical School and Massachusetts Institute of Technology Cambridge, Massachusetts 02139
4Department of Molecular Genetics
University of Maryland, College Park, Maryland 20742

The heterochronic genes lin-14, lin-28, and lin-42 cause precocious expression of LIN-29 during the L3 stage, whereas loss-of-function mutations in the gene lin-41 abolish upregulation of lin-29 (Bettinger et al., 1996).

The lin-14 gene regulates cell fate decisions during the early larval stages by generating a temporal gradient of LIN-14 protein during the L3 stage (Ruvkun and Giusto, 1989). High LIN-14 protein levels during the L1 stage specify L1 fates, and low LIN-14 levels specify L2 fates (Ambros and Horvitz, 1987). Because LIN-14 is a nuclear protein, it is likely to regulate the expression of genes that mediate L1-specific versus L2-specific patterns of cell lineage. The downregulation of LIN-14 is mediated during the late L1 stage (Feinbaum and Ambros, 1999) by the lin-4 regulatory RNA (Lee et al., 1993), which is complementary to several sites in the lin-14 3′ UTR (Wightman et al., 1991, 1993; Ha et al., 1996).

The lin-14 gene functions in temporal patterning during the L1 stage, long before the subsequent L4 stage upregulation of LIN-29, which controls the expression of adult-specific characters (Ambros and Horvitz, 1984). We screened genetically for novel heterochronic genes that act to couple activity of lin-14 at the L1 stage to lin-29 at the L4 stage. We sought such genes by genetic suppression of the heterochronic mutant phenotype of a relatively late-acting heterochronic mutant, let-7. Let-7 encodes a 21 nucleotide regulatory RNA that is expressed during the L3 and later stages and regulates temporal events at these late stages (Reinhart et al., 2000). Let-7 mutations cause reiterated late larval cell lineage transformations and interfere with normal temporal activation of LIN-29 expression (Reinhart et al., 2000). We identified seven lin-41 alleles as genetic suppressors of the let-7 retarded heterochronic and lethal phenotypes. Here we describe the molecular basis for the temporal patterning activity of the lin-41 heterochronic gene. We present molecular and genetic evidence that lin-41 acts in a genetic pathway of temporal control between the let-7 regulatory RNA and the lin-29 transcription factor.

Summary

Null mutations in the C. elegans heterochronic gene lin-41 cause precocious expression of adult fates at larval stages. Increased lin-41 activity causes the opposite phenotype, reiteration of larval fates. let-7 mutations cause similar reiterated heterochronic phenotypes that are suppressed by lin-41 mutations, showing that lin-41 is negatively regulated by let-7. Lin-41 negatively regulates the timing of LIN-29 adult specification transcription factor expression. lin-41 encodes an RBCC protein, and two elements in the lin-41 3′ UTR are complementary to the 21 nucleotide let-7 regulatory RNA. A lin-41::GFP fusion gene is downregulated in the tissues affected by lin-41 at the time that the let-7 regulatory RNA is upregulated. We suggest that late larval activation of let-7 RNA expression downregulates LIN-41 to relieve inhibition of lin-29.

Introduction

Heterochronic mutations have revealed a dedicated pathway that coordinates the temporal sequence of cell division and differentiation in many C. elegans cell types and tissues. These mutations cause cells to adopt fates normally expressed at earlier or later stages of development. The heterochronic genes lin-4, lin-14, lin-28, lin-42, and lin-29 form a genetic pathway to control stage-specific patterns of cell division and differentiation (Ambros and Horvitz, 1984; Ambros and Moss, 1993; Slack and Ruvkun, 1997). The upstream genes in the pathway regulate the normally L4 stage expression of the LIN-29 transcription factor that activates adult-specific cell differentiation. Loss-of-function mutations in

Notes

4To whom correspondence should be addressed (e-mail: ruvkun@frodo.mgh.harvard.edu).
5Present address: Axys Pharmaceuticals, NemaPharm Division, 180 Kimball Way, South San Francisco, California 94080.
6Present address: Department of Cell Biology and Molecular Genetics, University of Maryland, College Park, Maryland 20742.
7Present address: Department of Molecular, Cellular, and Developmental Biology, Yale University, New Haven, Connecticut 06520.
suppress the lethality of let-7(n2853) and identified 50 such mutations as detailed in Experimental Procedures. The F1 screen was expected to produce only dominant suppressor mutations, while the F2 screen was expected to produce both dominant and recessive suppressor mutations. One class of mutants, represented by seven independent isolates, was distinguished because they showed semidominant suppression of the lethality (Figure 1, Table 1, and data not shown) and the heterochronic defects (Table 1 and data not shown) of let-7 mutations. We also performed a screen for new precocious heterochronic mutants in a strain that has been shown to cause high frequencies of transposon insertion and point mutations (Collins et al., 1987) and isolated one mutant, ma104. Genetic mapping and complementation tests showed that these mutations are all alleles of the same gene, lin-41 (see below).

lin-41 Mutants Display a Precocious Heterochronic Defect

The lin-41 mutations caused recessive precocious heterochronic expression of an adult-specific hypodermal cell fate (Table 1). In wild-type animals, the lateral hypodermal seam cells divide with a stem cell-like pattern during the L1, L2, L3, and L4 stages before exiting the cell cycle and terminally differentiating after the L4 molt—a process termed the larval-to-adult (L/A) switch. These cells secrete a cuticular structure known as lateral alae at the adult stage (Figure 1). In mutants homozygous for the lin-41(n2914) null allele (see below) as well as in lin-41(ma104) mutants, 50% of animals exhibited precocious terminal differentiation of the seam cells at the L3 molt (Table 1). An average of five seam cells (out of a possible 15) displayed the precocious phenotype in lin-41(n2914) animals (n = 15 animals) at the L4 stage. We examined lateral hypodermal seam cells (V cells and descendants) at different stages during development and found that seam cell development in hermaphrodites proceeded normally until the L3 molt, when some seam cells precociously underwent the L/A switch (Figure 1).

lin-41(n2914) animals carrying a lin-41(+) transgenic array (C12C8 in Figure 3A) and presumably containing a higher than normal dosage of lin-41, showed a retarded phenotype in the hypodermis (59%, n = 53 animals), while control animals did not (data not shown). In retarded animals, most hypodermal seam cells failed to execute the L/A switch (i.e., exit the cell cycle and terminally differentiate) at the L4 molt and instead reiterated the larval fate and divided again (Figures 2B–2E). In some cases, the animals died by bursting through the vulva in a manner that resembled the lethality caused by loss of let-7 function (Reinhart et al., 2000). A similar retarded phenotype was observed in wild-type animals carrying a full-length lin-41 gene fused to the green fluorescent protein (GFP) (see Figure 5D legend), while control animals carrying just the injection marker did not display a retarded phenotype (data not shown). Thus, overexpression of lin-41 caused a heterochronic defect opposite to that of animals missing lin-41 gene activity, showing that LIN-41 is necessary and sufficient for the repression of adult-specific fates during earlier larval stages. lin-41 may act as a genetic switch to regulate developmental timing in the hypodermis. These data also argue that lin-41 is the major let-7 regulated output for heterochronic patterning.

lin-41(n2914) and lin-41(mg187) behaved genetically as null alleles; both caused a complete recessive sterility as homozygotes or in trans to a deficiency that removes lin-41, ndf24 (Table 1, data not shown). lin-41(ma104) did not behave as a null allele; lin-41(ma104) animals were fertile while lin-41(ma104)/ndf24 animals had a
Figure 1. The lin-41 Phenotype

(A–D) The lin-41 phenotype (magnification 50×). (A) Wild-type adult. (B) let-7(n2853) adults die by bursting through the vulva before producing progeny. (C) A lin-41(n2914)/let-7(n2853) adult is viable, but shows eggs accumulating in the animal. (D) A lin-41(n2914); let-7(n2853) adult is viable, but sterile and slightly Dpy. (E) Lateral view of the adult cuticle from a let-7(n2853) animal showing the lack of horizontal adult alae caused by the heterochronic defect (1000×). (F) Lateral view of the adult cuticle from a lin-41(n2914); let-7(n2853) animal showing restored adult alae (arrow). (G and H) lin-41 mutants lack oocytes (magnification 400×). Wild-type adult (G) viewed by Nomarski optics showing one arm of the gonad with sperm and oocytes. lin-41(n2914) adult (H) gonad with sperm but no oocytes. (I and J) lin-41 is required for proper timing of appearance of LIN-29 (magnification 630×). Wild-type L3 stage animals (I), which did not accumulate detectable levels of LIN-29 protein as viewed with antibodies to LIN-29. lin-41(n2914) L3 stage animal (J), which expressed high levels of LIN-29 protein, normally seen only at the L4 and adult stages. Anterior is to the left, and except for (J) ventral is down. In (J), ventral is toward the viewer.

more severe, sterile phenotype (Table 1). The classification of lin-41(n2914) as a null allele is supported by molecular analysis (see below). Observation of the gonads in lin-41(n2914) mutant animals using Nomarski optics revealed that sperm production appeared to be normal but that oocyte production was severely impaired (Figure 1). The defect in oocyte production is likely to be the cause of the sterility.

LIN-41 is a Member of the RBCC Family

lin-41(n2914) maps to chromosome I just to the left of mec-8. (Figure 3, Experimental Procedures). Cosmids spanning the genetic region to the left of mec-8 were tested for complementation of a lin-41 mutation in transgenic lines. The sterility and precocious heterochronic phenotype of lin-41(n2914) animals were partially rescued by cosmid C12C8, but not by the neighboring overlapping cosmid F26H9 (Figure 3A). A 14.5 kb PCR product that includes only one identified gene, C12C8.3 (accession number EMBL Z81467) (Hodgkin et al., 1995), also rescued the lin-41 phenotype (Figure 3A).

We identified mutations associated with lin-41 alleles in C12C8.3. lin-41(n2914) is a deletion of 50 nucleotides (Figures 4B and 4C) that is predicted to cause a frameshift that truncates the LIN-41 protein N-terminal to conserved regions and is predicted to produce a polypeptide of 138 amino acids instead of the normal products of 1143 and 1146 amino acids (see below). The genetic evidence that lin-41(n2914) is a null allele supports the prediction that this mutation truncates essential regions from LIN-41. The lin-41(ma104) allele has a Tc1 transposon inserted at amino acid 713. Five other lin-41 mutations cause substitutions in the C-terminal conserved region of the protein (Figure 3 legend, Figure 4). lin-41(mg187) results in an alteration on a Southern blot probed with C12C8 (data not shown), suggesting that this mutation is a DNA rearrangement. We did not identify the endpoints of this lesion.

By cDNA analysis, lin-41 is predicted to encode two nearly identical proteins, LIN-41A and LIN-41B, of 1143 and 1146 amino acids respectively, the result of an alternate splice acceptor site before the nonconserved region in exon 9 (Figure 3B) (accession numbers AF195610 and AF195611, respectively). LIN-41 is a member of a large family of RBCC (RING finger, B box, coiled coil) proteins (Figure 4A). Both LIN-41 products contain an N-terminal RING finger (Freemont, 1993) (a zinc-chelating domain thought to be involved in protein-protein
Figure 2. Cell Lineage Defects in lin-41 Mutants
(A) Cell lineages of the lateral hypodermal V cells in wild-type and lin-41(ma104) animals. The vertical axis indicates the four postembryonic larval stages divided by molts. In wild-type animals, the V1-4 cells divide near the beginning of each larval stage until the final molt, when they terminally differentiate and secrete adult-specific cuticular alae (termed the L/A switch), indicated by the triple bars. In lin-41(ma104) animals, the V1-4 cells can precociously execute the L/A switch at the L3 molt. By anatomical observation, lin-41(n2914) null mutants displayed the same late cell lineage defect. Specifically, we synchronized lin-41(n2914)/unc-29 lin-11 animals by hatching eggs in the absence of food, and the hypodermal seam cells of these animals (1/4 of which were predicted to be homozygous mutant for lin-41) were counted and found to be normal at early larval stages (# animal sides counted: mid-L1 [n = 99]; mid-L2 [n = 23]; mid-L3 [n = 19]). In addition, seam cells were also counted from homozygous lin-41(n2914) (mid-L4, n = 8 animal sides) and early adult (n = 6 animal sides) animals and were found to be normal. lin-41 mutants had a molting defect and sometimes failed in ecdysis at the final molt (data not shown). (B-D) lin-41 overexpression causes a retarded phenotype. In wild-type animals at the L4/adult molt, seam cells terminally differentiate, fuse (B) as observed with MH27 antibody, which recognizes a cell junction molecule (Labouesse, 1997), and secrete cuticular alae (D) indicated by a small arrow. In animals with increased lin-41(+) gene dosage (lin-41++), most seam cells reiterate the L4 stage larval fate at this time, divide again, and fail to fuse (B), or produce adult alae (E). A break in the alae is indicated between two large arrows. Magnification is 1000×.
**Lin-41 Control of Temporal Patterning**

663

Figure 3. The lin-41 Genetic Region

(A) lin-41 was mapped to LG I between the right end points of deficiencies nDf24 and nDf23. Cosmid C12C8 and a 14.5 kb PCR product containing only one identified gene, C12C8.3, partially rescued the sterile and heterochronic phenotype of lin-41—85% of C12C8 transgene-containing lin-41(n2914) animals from one line were rescued, and this line was fertile, although with a reduced brood size relative to wild type (data not shown). The neighboring cosmid F26H9 did not rescue. (B) The intron/exon structure of lin-41 and notable domains. An alternative splice acceptor site results in two transcripts: lin-41A (above) is 12 nucleotides shorter than lin-41B (below). The relative positions of lin-41 alleles are shown: n2914 is a deletion from 21767 to 21817, ma104 is a transposon insertion (Tc1) at position 17754, and the remaining mutations cause substitutions in the NHL domain (mg181, C-to-T at position 16985 [R-to-W]; mg182, G-to-A at position 16649 [R-to-Q]; mg184, C-to-T at position 17180 [T-to-I]; numbering is based on cosmid C12C8—accession number EMBL Z81467). The RING finger, B box, coiled coil, and NHL domains are indicated. Potential binding sites for the lin-4 and let-7 RNAs are shown in the 3' UTR. (C) The molecular lesion in the lin-41(n2914) null allele. In the lin-41(n2914) mutant, the wild-type sequence underlined is deleted, leading to a frameshift predicted to result in a premature stop codon. The bold residues indicate splice donor and acceptor sites of an intron in the RING finger region of lin-41. The Cys and His residues that make up part of the RING finger are in italics. (D) Potential RNA:RNA duplexes between lin-41 and let-7 RNAs, identified by a combination of manual searching and computer analysis using the FOLDRNA program of the GCG software package (Devreuses et al., 1984).

...the possible Drosophila and vertebrate LIN-41 orthologs (but not more distantly related RBCC proteins such as KIAA0517) conserve a very similar pattern of amino acid residues on the NHL domain, also endorsing their assignment as orthologs.

While these possible LIN-41 orthologs have unknown functions and biochemical mechanisms, other RBCC superfamily members suggest possible mechanisms of lin-41 gene function. The RBCC protein 52 kDa SS-A/Ro lupus autoantigen is cytoplasmic and associates with RNA (Chan et al., 1991). The RBCC protein HT2A binds to the HIV Tat transactivator, itself an RNA binding protein (Fridell et al., 1995). The C. elegans NCL-1 RBCC protein is a cytoplasmic protein that regulates ribosomal RNA and rRNA synthesis (Frank and Roth, 1998) through an unknown mechanism. Thus, LIN-41 is a potential RNA binding protein that could directly bind to, for example, the lin-29 mRNA (see below). In contrast, the RBCC mammalian oncoproteins PML (de The et al., 1991; Kizuki et al., 1991; Wang et al., 1998) and TIF1 (Le Douarin et al., 1995) are nuclear factors that are thought to regulate transcription. Recently, RING domains have been found in subunits of the E3 ubiquitin ligase (Iozzeiro et al., 1999; Seol et al., 1999; Tyers and Willems, 1999), suggesting an alternative model in which LIN-41 may regulate LIN-29 stability.

**Lin-41 Is Required for Temporal Regulation of LIN-29 Expression**

The expression of the LIN-29 zinc finger transcription factor is normally activated at the L4 and later stages in hypodermal cells and is necessary for the L4-to-adult stage differentiation of these cells (Ambros and Horvitz, 1984; Bettinger et al., 1996). Our genetic and molecular epistasis studies support a model in which lin-41 negatively regulates lin-29 to control the cessation of the molting cycle and the switch to adult hypodermal cell fates. The precocious heterochronic defect of lin-41 mutants required a wild-type copy of the lin-29 gene, since lin-41; lin-29 double mutants did not display a precocious defect and rather displayed the retarded defect characteristic of lin-29 mutants (Table 1). This finding suggests that lin-41 negatively regulates lin-29 in the hypodermis.

Molecular studies also favor the model in which lin-41 negatively regulates lin-29. LIN-29 protein was precociously expressed in lin-41(n2914) mutants at the L3 stage and, in some animals, at the L2 stage (Figures 3A and 3B) suggesting an alternative model in which LIN-41 may regulate LIN-29 stability.
Figure 4. LIN-41 Relatives

(A) LIN-41 is a divergent member of the RBCC family. (B) The amino acid sequence of LIN-41A in an alignment with the partial sequence of both a mouse gene (corresponding to the ESTs AA930787 and AA919390) and a predicted Drosophila gene (AC004280). The RING finger, B1 box and B2 box regions are underlined in succession. The NHL repeats are indicated by arrows; º indicates that the sequence is likely to continue but is not known at this time; º indicates gaps in the alignment; º indicates the end of an amino acid sequence. The amino acid changes caused by mutations in five lin-41 mutants are indicated. mg186 may disrupt a potential Ser/Thr phosphorylation site. TBLASTN against GenBank with the partial mouse gene shown above gave the following hits: LIN-41 p value $3 \times 10^{-71}$; Drosophila AC004280 $9 \times 10^{-69}$; KIAA0517 $1 \times 10^{-69}$. Accession numbers NCL-1 (GenBank AF047027), F54G8.4 (SWISS-PROT Q03601), F26F4.7 (GenBank U12964), HT2A (SWISS-PROT Q13049), KIAA0517 (DDBJ AB011089), PML (GenBank S50913), TIF1 (GenBank AF009353), SSA/Ro (GenBank M62800), and rpt (SWISS-PROT P15533). (C) Alignment of C. elegans LIN-29 zinc finger region with one of 2 possible Drosophila LIN-29 proteins (GenBank accession # AF173847 p value $3.8 \times 10^{-4}$) and Rat CIZ (DDBJ AB019281 p value $3 \times 10^{-4}$). The other possible Drosophila LIN-29 homologs...
Expression Pattern of lin-41

To determine which cells express lin-41, we fused the green fluorescent protein (GFP) gene to the N terminus of the full-length lin-41 gene (Figure 5C) and introduced this construct into wild-type C. elegans. This construct rescued a lin-41 mutant and caused a gain-of-function phenotype in wild-type animals (Figure 5 legend), suggesting that the construct encoded a functional product. LIN-41/GFP expression was observed in most C. elegans neurons (Figure 5A), in body wall and pharyngeal muscles, and in the lateral hypodermal seam cells (Figure 5B). LIN-41/GFP was predominantly cytoplasmic. In neurons, muscle, and pharangeal cells, LIN-41/GFP was expressed at all stages, from late embryogenesis until adulthood. In hypodermal seam cells, LIN-41/GFP expression faded during the L4 stage (Figure 5D) at a time when genetic analysis suggests that activation of the let-7 regulatory RNA inhibits lin-41 gene activity. Molecular evidence favors a direct role for let-7 RNA in regulation of lin-41 (see below).

LIN-41/GFP was also expressed in the somatic gonad throughout postembryonic development, and was expressed in the spermatheca, the distal tip cells, and certain uterine cells in late larval and adult animals (data not shown). The somatic gonad might be the site of action of LIN-41 in promoting oocyte development (Figure 1).

The 3’ UTR of lin-41 Is Sufficient for Downregulation of lin-41

let-7 encodes a small regulatory RNA that is necessary for upregulation of lin-29 expression and for specification of adult stage cell fates (Reinhart et al., 2000). let-7 expression begins just prior to the L4 stage, when lin-41 is downregulated. Given that lin-41 alleles were identified as suppressors of let-7 alleles and that two zygotic doses of lin-41 are necessary for the let-7 lethality and retarded defects, we postulated that the let-7 RNA may directly regulate lin-41. We identified two sequences in the lin-41 3’ UTR complementary to the let-7 RNA (Figure 3D). The lin-41 3’ UTR was placed 3′ to the E. coli lac-Z gene driven by the hypodermally expressed col-10 promoter. This reporter gene was temporally regulated in a similar manner to the lin-41 gene itself. ß-galactosidase activity was observed in larval animals but was mostly absent in adult animals (Figure 5C). The adult stage downregulation of the col-10/lacZ fusion gene was dependent on the lin-41 3’ UTR, because a control fusion gene bearing the nonheterochronic gene unc-54 3’ UTR was expressed at all stages including the adult stage (Wightman et al., 1993). let-7 and the let-7 complementary sites in the lin-41 3’ UTR were required for the downregulation (Reinhart et al., 2000). These experiments show that the let-7 complementary sites in the lin-41 3’ UTR mediate the downregulation of LIN-41 during the L4 and later stages in the hypodermis.

The heterochronic gene lin-4 also encodes a small RNA that binds to complementary sequences in the 3’ UTR of the mRNAs of lin-14 and lin-28 to downregulate their expression. The lin-41 3’ UTR also contains a site with complementarity to the lin-4 RNA (Figure 3D). However, lin-4 may not play a significant role in regulating lin-41, as the lin-4(0) retarded phenotype was not affected by removal of lin-41. Specifically, the lin-41(0); lin-4(0) double mutant animals displayed the lin-4 heterochronic phenotype in the hypodermis and vulva (data not shown).

Discussion

Based upon the lin-41 null phenotype and the epistasis relationships among lin-41, let-7, and lin-29 mutations, we conclude that lin-41 functions in temporal patterning during late larval stages, and that lin-41 acts downstream of the let-7 regulatory RNA and upstream of the LIN-29 transcription factor. Loss-of-function mutations in lin-41 cause precocious terminal differentiation of hypodermal seam cells one larval stage earlier than normal, while overexpression of lin-41 causes terminal differentiation to be delayed. Thus, lin-41 is necessary and sufficient to prevent terminal differentiation of seam cells and to promote their cell division.

Consistent with this proposed regulatory role, lin-41 encodes a member of the RBCC family of regulatory proteins, some of which have been implicated in RNA binding or control of RNA function. For example, the RBCC family member 52 kDa SS-A/Ro, an autoantigen in Sjogren’s syndrome, is cytoplasmically localized (Pourmand et al., 1998) and binds to a particular small RNA (Chan et al., 1991), while the C. elegans NCL-1 RBCC protein regulates nucleolus size and rRNA abundance (Frank and Roth, 1998). Additionally, the MDM2 oncoprotein (with a RING finger but no BCC domain) binds RNA directly through the RING finger domain (Elenbaas et al., 1996). The biochemical assignment of RBCC protein function to RNA regulation, plus our finding that a lin-41::GFP fusion gene is cytoplasmically localized, suggest that LIN-41 may regulate the translation of other heterochronic genes. LIN-41 may have additional targets in the gonad that control fertility (see below). RING finger proteins are also important subunits of the E3 ubiquitin ligase (O’ozeiro et al., 1999; Seol et al., 1999; Tyers and Willems, 1999).

The wild-type activity of LIN-29 is required for the precocious defect of lin-41 mutations (Table 1) and the time of LIN-29 protein expression is regulated by lin-41 (Figure 1), suggesting that the lin-29 mRNA may be a direct target of lin-41. During wild-type development, LIN-29 protein is first detected during the L4 stage, when it specifies the adult-specific expression of particular
collagen genes, the cessation of the molting cycle, and fusion rather than division of hypodermal seam cells (Ambros and Horvitz, 1984). However, the lin-29 mRNA accumulates much earlier, starting at the L2 stage (Rougvie and Ambros, 1995; Bettinger et al., 1996). Thus, during normal development, the translation of lin-29 mRNA appears to be negatively regulated until the L4 stage, restricting the time of the L4-to-adult transition to the time of LIN-29 protein expression. An attractive model is that LIN-41 directly binds to the lin-29 mRNA and inhibits its translation during early larval stages (Figure 6). LIN-41 contains domains that are implicated in RNA binding, and is expressed in the correct cellular compartment and at the correct time (L2 and L3 stage).
LIN-41 Control of Temporal Patterning

667

A. lin-4 — lin-14/28 — let-7 — lin-41 — lin-29

B. Levels

lin-29 mRNA

LIN-41 protein

LET-7 RNA

L1
L2
L3
L4
Adult

Figure 6. Model of Heterochronic Gene Activities in the Hypodermis
(A) Genetic data support a model whereby the heterochronic gene let-7 negatively regulates lin-41, which in turn negatively regulates lin-29. let-7 is likely to respond to the earlier action of lin-14/lin-28. The simplest interpretation of the data is consistent with a linear pathway as shown.
(B) lin-29 mRNA appears during the L2 stage, but LIN-29 protein is first observed during the L4 stage. Molecular data suggest that lin-41 activity is required for the post-transcriptional repression of lin-29 during the L2 and L3 stages. lin-41 expression may itself be translationally regulated by the appearance of the let-7 RNA. lin-41 and lin-29 are represented in the other animals, raising the possibility that the mechanism of temporal patterning may be conserved.

to function in this role. The precocious heterochronic lin-41 mutant phenotype may be caused by a loss of the normal lin-41 mediated repression of lin-29 mRNA translation during the L2 and L3 stages. The RING finger of LIN-41 suggests an alternative model that it may regulate LIN-29 stability. Although lin-29 is expressed in the L2 stage in lin-41(lf) animals, there is no adult alae formation at the L2 molt. This suggests that either lin-41 is not sufficient for adult fates in the L2, and/or that lin-29 is regulated posttranslationally.

lin-41 is not only necessary for the earlier repression of LIN-29 expression, but we speculate that it is also sufficient to induce that repression at later stages, since high lin-41 gene dosage causes a delay in the larval-to-adult switch. Thus, the downregulation of lin-41 gene activity during the L4-to-adult transition may be critical to the upregulation of lin-29 gene activity. A likely trigger for lin-41 downregulation during the L4 stage, which we observed in the hypodermis with a lin-41::GFP fusion gene (Figures 5 and 6), is the upregulation of the let-7 regulatory RNA during the L3 and L4 stages. lin-41 is a major target of let-7 regulation; lin-41 mutations strongly suppressed the retarded heterochronic and lethal phenotypes of let-7 mutants, and high lin-41 gene dosage caused the same heterochronic and lethal phenotypes as did loss of let-7. let-7 encodes a small RNA that is expressed beginning during the L3 stage and functions during the L4 stage to control indirectly the translation of the LIN-29 protein, which in turn regulates the switch to adult hypodermal fates (Reinhart et al., 2000). Consistent with a direct regulation of lin-41 by let-7 is our finding of let-7 complementary sequences in the lin-41 3' UTR, suggesting that let-7 directly negatively regulates lin-41 by binding to the 3' UTR of lin-41. The time of let-7 expression and function appears to be just before the time of LIN-41 protein downregulation in the hypodermis and function during the L4-to-adult molt.

The lin-41 3' UTR was sufficient to downregulate a heterologous reporter gene (Figure 5), and we found that let-7 and the let-7 complementary sequences in the lin-41 3' UTR were required for this downregulation (Reinhart et al., 2000). These observations strongly suggest that let-7 functions to bind directly to the 3' UTR of lin-41 mRNA and inhibit lin-41 expression. Thus, lin-41 transduces temporal information from a regulatory RNA to a transcriptional output, LIN-29.

We propose that in a let-7 mutant, LIN-41 protein is misexpressed in time, and that this misexpression causes the let-7 heterochronic defects and lethality. Since animals heterozygous for the lin-41 null mutation in trans to a wild-type allele can potentially suppress the heterochronic and lethal phenotypes of a let-7 null mutant, lin-41 is dosage-sensitive for the retardation of lin-29 gene action in the let-7 mutant. This is consistent with the hypothesis that LIN-41 has a structural or stoichiometric function as opposed to a catalytic function (Smustad, 1968). Perhaps the concentration of LIN-41 relative to a threshold is critical, and the role of let-7 is to repress LIN-41 to below-threshold levels.

lin-41 is unlikely to be the sole input to lin-29 temporal regulation. The precocious phenotype of lin-41 null mutant animals is neither 100% penetrant nor 100% expressive; not all animals exhibit a precocious phenotype and in those animals that do, not every seam cell expresses the precocious L/A switch defect. This observation suggests that additional genes can partially substitute for LIN-41 function. For example, there may be other let-7 regulatory outputs. In addition, there are three RBCC-NHL proteins predicted from the C. elegans genome sequence (Figure 5A) that may function in a partially redundant manner to provide additional temporal inputs to lin-29.

The heterochronic pathway involves at least three cases of posttranscriptional regulation. lin-14 and lin-28 messenger RNAs are expressed at all stages of postembryonic development, yet the proteins are expressed only at specific times (Wightman et al., 1993; Moss et al., 1997). The lin-4 small RNA with sequence complementarity to the 3' UTRs of lin-14, lin-28, and the let-7 small RNA with complementarity to lin-41 are thought to regulate translation of these mRNAs. Similarly, lin-29 mRNA is present from the L2 stage, but translated in the hypodermis only during the L4 stage and later stages (Rougvie and Ambros, 1995), after the levels of LIN-41 RBCC protein decline.

The inhibition of translation also plays a role in the control of the tra-2 and fem-3 genes, which regulate the switch between sperm and oocyte cell fates in C. elegans (Goodwin et al., 1993; Zhang et al., 1997). Although we have not examined directly whether lin-41 hermaphrodites are defective in the sperm/oocyte switch, the lack of oocytes is consistent with such a defect, and implies that LIN-41 could play a role in the translational regulation involved in this germline cell fate choice. LIN-41/GFP is expressed in multiple cell types in the somatic gonad, where it could act to affect this switch.

Of the known C. elegans heterochronic genes, lin-41 (Figure 4B) and lin-29 (Figure 4C) (Rougvie and Ambros, 1995) show the most extensive sequence similarity to genes from other phyla. The mammalian and Drosophila
genes with a high degree of sequence identity to lin-41 and lin-29 define possible orthologs that may have similar functions in temporal patterning. Time will tell whether any of these orthologs also play roles in the control of developmental timing.

Experimental Procedures

Phenotype Analysis
To observe the extent of alae formation in larval and adult stages, living animals were observed using Nomarski optics. L4 stage animals and young adults were identified by their gonadal development (Hirsh and Vanderslice, 1976), which is not affected by the heterochronic mutations used in this study (Ambros and Horvitz, 1984). The extent of alae formation was judged on a single side of each animal. Anti-LIN-29 antibody staining was performed as described (Bettinger et al., 1996). Animals were grown at 15°C prior to staining. Cell lineage analysis was performed as described (Sulston and Horvitz, 1977).

Isolation and Characterization of Novel Precocious Mutants
let-7(n2853ts) mutants were grown at the permissive temperature (15°C) and subjected to ethylmethane sulfonate (EMS) mutagenesis. In two separate screens, the F1 progeny (F1 screen for dominant suppressors) or F2 progeny (F2 screen for recessive suppressors), respectively, of mutagenized animals were raised at the nonpermissive temperature (25°C) and reproducing animals were picked from a background of let-7 lethal mutant animals. F1 screen: from 12,000 mutagenized haploid genomes, 10 independently isolated lethals were obtained. F2 screen: from approximately 10^4 mutagenized haploid genomes, 40 independently isolated lethals were obtained. Additional spontaneously arising suppressor mutants were identified in the course of propagating unmutagenized let-7(n2853) animals. These mutations fall into a number of different classes: one class (mg181, mg182, mg183, mg184, mg186, mg187, and n2914), which shows dominant suppression of the let-7 lethality, is the subject of this paper; the others will be described elsewhere (F. J. S., unpublished data). let-7(n2853) animals heterozygous for the lin-41 alleles, mg187 and n2914, were slightly egg-laying defective (Egl) and were observed to segregate approximately 1/4 dumpy (Dpy) sterile (Ste) animals (lin-41; let-7), as well as 1/4 dead Let-7 animals (lin-41; let-7), suggesting that the mg187 and n2914 mutations semidominantly suppressed the lethality of let-7, and that they displayed a recessive Dpy Ste phenotype. mg181, mg182, mg183, mg184, and mg186 are not recessive sterile, but can also dominantly suppress let-7 (data not shown). lin-41(n2914) was isolated from the mutator strain TR679 as a precocious heterochronic mutant.

Mapping of lin-41 and Complementation Tests
lin-41(n2914) was mapped to the unc-29 lin-11 interval on LGI by standard genetic tests: from lin-41(n2914)/unc-29(e1072) lin-11(n2281) animals, 8/10 Lin-11 non-Unc recombinants segregated Lin(n2914) animals. lin-41(n2914) was shown to be linked to unc-29 on LGI by standard genetic tests. lin-41(n2914) was shown to map to the right of lin-28: from lin-41(n2914)/dpy-5 lin-28 1/45 Lin(n2914) animals through Dpy Non-Lin-28 recombinants, and 1/45 Lin(n2914) animals through Dpy Lin-28 recombinants. This result suggests that lin-41(n2914) maps very close either to the left or to the right of lin-28. The heterochronic and fertility defects of lin-41 are recessive. Deficiencies dN30, mdN12, and dN24 failed to complement lin-41 mutations for the Dpy sterile phenotype, but dN23 complements lin-41(n2914). These data position lin-41 to a very small region of the genome, between aph-1 and mec-8. lin-41(n2914) failed to complement lin-41(n2914), but complemented mutations in other genes in this region of the genetic map.

Cloning of lin-41
Cosmids were isolated from the cosmid libraries of the Ruvkun laboratory for critical reading of this manuscript. H. R. H is an Investigator of the Howard Hughes Medical Institute. This work was supported by NIH R01 grant (GM44619) to G. R., an NRSA postdoctoral fellowship (GM18663) to F. S., an NIH R01 grant GM24663 to H. R. H., a U. S. Public Health Service Grant GM34028 to Z. L. and V. A., and by the HHMI (M. B. and H. R. H.)

Received March 30, 1999; revised February 10, 2000.

References


