Direct regulation of egl-1 and of programmed cell death by the Hox protein MAB-5 and by CEH-20, a C. elegans homolog of Pbx1

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Hox genes are crucial determinants of cell fates and of body morphology of animals; mutations affecting these genes result in abnormal patterns of programmed cell death. How Hox genes regulate programmed cell death is an important and poorly understood aspect of normal development. In the nematode C. elegans, the Hox gene mab-5 is required for the programmed cell deaths of two lineally related cells generated in the P11 and P12 lineages. We show here that in the P11 lineage, a complex between MAB-5 and the Pbx homolog CEH-20 directly regulates transcription of the BH3 domain gene egl-1 to initiate programmed cell death; in the P12 lineage, mab-5 and ceh-20 apparently act indirectly to initiate programmed cell death. Direct regulation of programmed cell death may be an evolutionarily ancient and conserved function of Hox genes.

KEY WORDS: C. elegans, Hox genes, Programmed cell death

INTRODUCTION

Hox proteins specify cell fates along the anteroposterior body axis in metazoans. In many organisms, including C. elegans, Drosophila and mammals, mutations that affect Hox gene function result in abnormal patterns of programmed cell death (Bello et al., 2003; Clark et al., 1993; Economides et al., 2003; Gavalas et al., 2003; Kenyon, 1986; Lohmann et al., 2002; Miguel-Aliaga and Thor, 2004; Salser et al., 1993; Stadler et al., 2001). Programmed cell death is a widespread and, in most organisms, essential aspect of normal development; mutations that influence whether cells survive or undergo programmed cell death contribute to human disease. Discovering how Hox genes regulate programmed cell death is therefore important for understanding the roles of Hox genes in development and disease.

As homeodomain-containing proteins, Hox proteins are likely to act by regulating transcription. The crucial task is therefore to identify those targets regulated by Hox proteins that determine programmed cell death or survival of individual cells or groups of cells. At present, it is not clear whether, for example, the abnormalities in programmed cell death observed in Hox mutants represent transformations in cell fate that then indirectly manifest as abnormal patterns of programmed cell death, or whether Hox genes directly determine programmed cell death or survival by regulating transcription of cell death genes. Recent data in Drosophila indicate that the Hox protein Deformed directly regulates transcription of the proapoptotic gene reaper to induce programmed cell death and shape a morphological boundary (Lohmann et al., 2002). Whether this is a general function of Hox genes during development needs to be explored.

The genetic pathway for the execution of programmed cell death in C. elegans is well established and highly conserved across animal species (Metzstein et al., 1998). In addition, the essentially invariant pattern of development makes it possible to study cell fates at the level of individual cells (Sternberg and Horvitz, 1984). C. elegans therefore presents an excellent model in which to study the mechanisms that regulate cell fates and programmed cell death.

The C. elegans genome contains six Hox genes organized as three gene pairs in a contiguous region of chromosome III. As in other metazoans, the Hox genes of C. elegans are generally organized along the chromosome in the order in which they are expressed in the animal, with one exception (WormBase website, http://www.wormbase.org, release WS138, 11 February 2005) (Bruschwig et al., 1999; Clark et al., 1993; Wang et al., 1993). The six Hox genes include single genes orthologous to labial (celh-13), sex combs reduced (lin-39) and antennapedia (mab-5), and three posterior Hox genes (egl-5, php-3, nob-1) (Aboobaker and Blaxter, 2003; Van Auken et al., 2002; Wang et al., 1993). Three Hox genes, lin-39, mab-5 and egl-5, for which mutants bearing null alleles are viable, have been extensively characterized (Chisholm, 1991; Clark et al., 1993; Kenyon, 1986; Wang et al., 1993). Mutations affecting these genes result in abnormal patterns of programmed cell death. Specifically, lin-39 is essential for the survival of six neurons, the VC neurons, generated in the midregion of the ventral nerve cord (Clark et al., 1993), and mab-5 is essential for the programmed cell death of two cells, P11.aap and P12.aap, generated in the posterior ventral nerve cord (Kenyon, 1986; Ph.aap, the posterior daughter of the anterior daughter of the anterior daughter of any P blast cell). In lin-39 mutants, the six VC neurons in the midbody of the ventral nerve cord express fates characteristic of their more anterior and posterior lineal homologs (lineal homologs are cells arising at corresponding positions of related lineages, and they typically adopt related fates (Sulston and Horvitz, 1977)), which undergo programmed cell death, suggesting lin-39 provides spatial information to the developing animal (Clark et al., 1993) and consistent with the functions of Hox genes in other animals (McGinnis and Krumlauf, 1992). A similar role has been suggested for mab-5 in the posterior ventral nerve cord, where the P(11,12).aaap cells of mab-5 mutants survive, as do their anterior lineal homologs (Kenyon, 1986).
How mutations in lin-39 and mab-5 determine cell death or survival is not yet known. Characterization of mab-5 mutants suggests that mab-5 function is necessary but not sufficient to specify programmed cell death of the P(11,12).aaap cells (Salser et al., 1993). For example, strong loss of function or null mutations in mab-5 result in survival only of P(11,12).aaap in the ventral nerve cord; programmed cell death of other cells in the ventral nerve cord occurs normally. In mutants that ectopically express mab-5, the anteriorly located lineal homologs of the P(11,12).aaap cells do not undergo programmed cell death (Salser et al., 1993). These experiments suggest the existence of factors that prevent programmed cell death of the P(11,12).aaap anterior lineal homologs or that act with mab-5 in P(11,12).aaap to ensure their death. Given the similarity in cell division patterns and fates of cells generated by the P11 and P12 lineages (Sulston and Horvitz, 1977), it was surprising to find that MAB-5 protein is detected in the P11 blast cell and the five cells ultimately generated by P11 including P11.aaap, but not in the P12 descendants after the first division (Salser et al., 1993). mab-5 might therefore determine cell fates through different mechanisms in the P11 and P12 lineages, including the P(11,12).aaap programmed cell deaths.

Hox proteins can bind DNA cooperatively with protein cofactors, including the PBC family of homedomain proteins (Chan et al., 1994). The PBC family, which includes Drosophila extradenticle and the mammalian Pbx proteins (Burglin, 1997), binds to a specific subset of Hox proteins via an interaction between a conserved hexapeptide motif found in the Hox protein (Chang et al., 1995) and a pocket in the cofactor (Piper et al., 1999). The C. elegans genome encodes two proteins similar to Pbx, CEH-20 and CEH-40 (WormBase web site, http://www.wormbase.org, release WS138, 11 February 2005), and the Hox proteins LIN-39 and MAB-5 both contain the hexapeptide motif required for interaction with PBC proteins. ceh-20 cooperates with lin-39 and mab-5 during mesoderm differentiation, where a LIN-39/CEH-20 heterodimer directly regulates the C. elegans homolog of twist (Liu and Fire, 2000), and ceh-20 and ceh-40 act partially redundantly during embryonic development (Van Auken et al., 2002). ceh-20 mutants have multiple defects in vulval development and neuronal migration that in part are similar to those of lin-39 mutants, but also have distinct defects that suggest lin-39-independent functions (Yang et al., 2005).

In C. elegans, the BH3 domain-encoding gene egl-1 is required for programmed cell death of somatic cells, and expression of egl-1 is sufficient to induce programmed cell death (Conradt and Horvitz, 1998). The EGL-1 protein physically interacts with the Bcl2 homolog CED-9 to initiate programmed cell death (Conradt and Horvitz, 1998). Two pathways are known that directly regulate expression of egl-1 and the programmed cell death of specific cells. In the HSN neurons, the TRA-1 transcription factor binds egl-1 regulatory sequences to prevent programmed cell death (Conradt and Horvitz, 1999). egl-1 mutations that prevent TRA-1 binding result in expression of egl-1 in the HSNs, their programmed cell death and an egg-laying defect. In a specific subset of pharyngeal neurons, the ces-2 and ces-1 genes act in a negative regulatory cascade to promote programmed cell death (Ellis and Horvitz, 1991). The Snail homolog CES-1 directly represses egl-1 in a process opposed by the BHLH proteins HLH-2 and HLH-3 (Thellmann et al., 2003). These data demonstrate that the fate of programmed cell death of specific cells can be determined by regulating transcription of egl-1.

We report here that, as part of its function in specifying fates in the P11 and P12 cell lineages, a complex containing the Hox cofactor and Pbx homolog CEH-20 and the Hox protein MAB-5 directly regulates egl-1 expression to induce programmed cell death of P11.aaap.

**MATERIALS AND METHODS**

**Genetic methods and strains**

Worms were maintained as described by Brenner (Brenner, 1974) at 20°C. The following mutations were used: LGL, ced-1(e1735); LGIII, mads16 (Cowling and Kenyon, 1996); LGIII, ceh-20(ay9), ceh-20(ay42) and unc-36(e251), unc-119(ed3); LGV, egl-1(n1084m3082); LGX, ceh-40(gk159). 

The strain NC216 containing the Pceh-20:gdpsfwdEx75 array and the NCI190 strain containing the Panum gfp wd6 integrated array were generously provided by David Miller (Vanderbilt University, Nashville, TN). ceh-20 alleles were a gift from M. Stern (Yale University, New Haven, CT). The ceh-40(gk159) allele was isolated and provided by the C. elegans Knockout Consortium (http://celeganskconsortium.omrf.org). The ceh-40(gk159) allele deletes 968 bp of genomic sequence including all of predicted exons 2, 3, 4 and 5. It was transcribed and translated, the deletion would be predicted to generate a truncated protein that includes the initial 31 amino acids of CEH-40 followed by missense amino acids and premature termination. Some nematode strains used in this work were provided by the Caenorhabditis Genetics Center, which is funded by the NIH National Center for Research Resources (NCRR). Lineage analysis was performed as described by Sulston and Horvitz (Sulston and Horvitz, 1977). Biologic bombardment was performed as described (Präfleit et al., 2001).

**Plasmid constructs**

The wild-type 7.6 kb egl-1 genomic region is contained in plasmid pBC08 (Conradt and Horvitz, 1998). Site-specific mutagenesis was performed using the method of Quickchange (Stratagene) and all DNA segments exposed to PCR or mutagenesis were fully sequenced. For the egl-1 transgene containing mutations in sites 1 and 2 and a deletion in the F23B12.1 coding sequences and the plasmid religated. To construct the pMP0017 Pceh-20:cdsfp translational fusion plasmid, a 3.6 kb Sall/PfI fragment of the ceh-20 genomic region, including 1 kb of 5' sequence and 1 kb of 3' sequence was amplified by long PCR and cloned into pBSKSII+. Site-specific mutagenesis was used to change the stop codon to an AscI restriction site, into which the cdsfp-coding region from pPD134.96 (kindly provided by Andy Fire, Stanford University, Palo Alto, CA) was cloned. This plasmid was injected at a concentration of 50 ng/μl into ceh-20(ay42), where it resced the egg-laying defect, and together with a lin-15-rescuing plasmid into ceh-3(n717); lin-15(n765) mutants. To construct the Pcdh-histone:gfp reporter, overlap PCR was used to replace the open reading frame of egl-1 by an Agel restriction site. A fusion of the R087C.3 histone 2A gene to gfp was inserted into the Agel site. This plasmid was microinjected into ced-3(n717); lin-15(n765) mutants at a concentration of 10 ng/μl and integrated after gamma irradiation. The mads14 integrated array was mapped to LG X.

**Fusion proteins and electrophoretic mobility shift assays**

Full length ceh-20 and mab-5 cDNAs amplified from wild-type C. elegans total RNA were cloned as MscI XhoI fragments generated by PCR into a derivative of pSP73 that contains the Xenopus β-globin 5' untranslated region (Swift et al., 1998). Oligonucleotides encoding the myc or FLAG epitope were then ligated into MscI-digested mab-5 or ceh-20 expression plasmids. Those regions of constructs generated by PCR or changed after ligation of the oligonucleotides were completely sequenced. Proteins were generated by coupled transcription and translation in vitro using SP6 polymerase and T7 wheat-germ extract (Promega) and efficiency of protein generation was estimated by synthesis of an aliquot including 35S-methionine followed by autoradiography (for native proteins) or after western blot (for epitope-tagged proteins). For EMSAs, proteins were preincubated for 15 minutes at 37°C in a 10 μl reaction including 20 mM HEPES (pH 7.9), 15% glycerol and 0.2 mM DTT, 5 mM MgCl2, 50 ng poly-dC-dC, 50 ng methionine followed by autoradiography (for native proteins) or after western blot (for epitope-tagged proteins). For EMSAs, proteins were preincubated for 15 minutes at 37°C in a 10 μl reaction including 20 mM
RESULTS

mab-5 determines aspects of identity in addition to promoting programmed cell death

The P11.aaap and P12.aaap cells are lineal equivalents of the VB motoneurons (Sulston and Horvitz, 1977), which express the predicted acetylcholine receptor subunit acr-5 and the sodium channel del-1 (Esmaeili et al., 2002; Winnier et al., 1999). We used gfp reporter constructs to examine expression of these markers in ced-3 mutants, in which the death of the P(11,12).aaap cells was prevented by a block in programmed cell death, and compared the results with those where death of the cells was prevented by mutation of mab-5. Thirty out of 30 animals of genotype P_del-1gfp; ced-3(n717) expressed gfp in P11.aaap, while only one out of 30 animals of genotype P_del-1gfp; mab-5(n1384) did so. Similarly, 24 of 30 animals of genotype P_acr-5gfp; ced-3(n717) expressed gfp in P11.aaap, while only two out of 30 animals of genotype P_acr-5gfp; mab-5(n1384) did so. These data suggest that mab-5 may determine aspects of P11.aaap identity in addition to inducing programmed cell death of the cell, or that it directly promotes expression of the acr-5 and del-1 transgenes.

The Hox co-factor ceh-20 regulates programmed cell deaths

Hox proteins can act with co-factors to alter their binding affinity and specificity (Mann and Affolter, 1998). ceh-20 and ceh-40 each encode homologs of the extradenticle/Pbx TALE class of homeodomain proteins (http://www.wormbase.org, release WS138, 11 February 2005). ceh-20 acts with lin-39 and mab-5 to pattern mesoderm (Liu and Fire, 2000), and redundantly with ceh-40 during embryonic development (Van Auken et al., 2002). ceh-20 mutants also have defects in neuronal migration that are in part similar to those in lin-39 mutants (Yang et al., 2005). In the ventral nerve cord, ceh-20 mutants have defects in programmed cell death consistent with loss of lin-39 function in the midbody and of mab-5 function in the posterior (Table 1). In mutants carrying the strong loss-of-function allele ceh-20(ay42) (M. Stern, personal communication; null alleles are lethal), the defects include programmed cell death of six cells in the midregion of the ventral nerve cord and survival of two cells in the posterior ventral nerve cord (Fig. 1). We followed cell lineages in ceh-20(ay42) mutants and directly observed programmed cell death of the VC neurons in the midbody, as in lin-39 mutants, and survival of the P(11,12).aaap cells, as in mab-5 mutants (Fig. 1). ceh-40(gk159) mutants have a normal pattern of cell deaths in the ventral nerve cord, and the defects in cell death in mutants carrying a weak allele of ceh-20, ay9 are not enhanced by

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Table 1. ceh-20 acts together with Hox genes to determine cell death and survival

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Anterior (W, P1, P2)</th>
<th>Midbody (P3-P8)</th>
<th>Posterior (P9-P12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ced-1</td>
<td>2.8±0.1</td>
<td>0</td>
<td>5.5±0.1</td>
</tr>
<tr>
<td>ced-1; egl-1(n1084n3082)</td>
<td>0.1±0.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ced-1; mab-5(e1239)</td>
<td>2.4±0.1</td>
<td>0</td>
<td>3.5±0.2</td>
</tr>
<tr>
<td>ced-1; ceh-20(ay42)</td>
<td>2.3±0.5</td>
<td>5.2±0.8 (range 4-6)</td>
<td>2.9±0.9</td>
</tr>
<tr>
<td>ced-1; ceh-20(ay9)</td>
<td>2.5±0.5</td>
<td>2.9±1.2 (range 1-6)</td>
<td>4.4±1.2</td>
</tr>
<tr>
<td>ced-1; ceh-40(gk159)</td>
<td>2.4±0.6</td>
<td>0</td>
<td>5.8±0.8</td>
</tr>
<tr>
<td>ced-1; ceh-20(ay9); ceh-40(gk159)</td>
<td>2.7±0.4</td>
<td>2.3±0.5 (range 1-5)</td>
<td>4.7±1.0</td>
</tr>
</tbody>
</table>

*The number of cell corpses in the indicated regions of the ventral nerve cord was determined by observation using Nomarski optics. In wild-type animals, there are three, zero and seven cell deaths in the anterior, midbody and posterior ventral nerve cord, respectively (Sulston and Horvitz, 1977). Mutation of ced-1 does not completely block engulfment (Ellis et al., 1991; Zhou et al., 2001) and engulfment contributes to cell killing (Reddien et al., 2001), accounting for the small differences between numbers of cell deaths and numbers of cell corpses in otherwise wild-type ced-1 mutants. The ced-1(e1735) allele was used in all strains. For all genotypes, n=30.
the *ceh-40*(**gk159**) deletion, suggesting that *ceh-40* is dispensable for determining the pattern of programmed cell death in the ventral nerve cord (Table 1). In contrast to the highly penetrant defects in *lin-39* and *mab-5* function, we did not observe any transformation of the P12 lineage to the P11 fate, as is observed in *egl-5* mutants (Chisholm, 1991), suggesting that *ceh-20* may not act as the co-factor for *egl-5* in this lineage.

**egl-1** expression correlates with the pattern of programmed cell death in the posterior ventral nerve cord

In some *C. elegans* cells, programmed cell death is regulated by controlling transcription of *egl-1*. To begin to determine whether Hox proteins might promote survival or programmed cell death of cells by directly regulating transcription of *egl-1*, we constructed a reporter transgene in which the *egl-1* open reading frame was replaced by a histone:gfp fusion (see Materials and methods) and examined expression of this reporter in wild-type and Hox mutant backgrounds. In wild-type transgenic hermaphrodites, expression of the reporter in the posterior ventral nerve cord matches the wild-type pattern of programmed cell deaths, with expression of *gfp* in one nucleus each generated by the P9 and P10 lineages, two nuclei generated by the P11 lineage, and three nuclei generated by the P12 lineage (Fig. 2; data not shown). In *mab-5* and *ceh-20* mutants (see below) the pattern of fluorescent nuclei is changed to match the pattern of programmed cell death in the mutants (Fig. 2; data not shown); specifically, the reporter is not expressed in P(11,12).aaap. These results are consistent with transcriptional regulation of *egl-1* to induce programmed cell death of these cells. The P(11,12).aaap cells do not undergo programmed cell death in *egl-1* mutants (Table 1) consistent with the essential role of *egl-1* in the programmed cell death of somatic cells (Conradt and Horvitz, 1998).

**Hox genes act upstream of or parallel to the cell death gene egl-1**

To address where in the genetic pathway for programmed cell death the Hox genes might act, we determined whether loss-of-function mutations in *egl-1* could prevent programmed cell deaths in *lin-39* mutants. The *P*~*lin-11*~*gfp* reporter construct is expressed in the six VC motoneurons of wild-type animals (Cameron et al., 2002). *lin-39*(**n1760**); *P*~*lin-11*~*gfp* mutants do not express the reporter in the midbody (Fig. 3), consistent with programmed cell death of the VC neurons in these mutants (Clark et al., 1993). In *lin-39*(**n1760**); *egl-1*(**n1084n3082**); *P*~*lin-11*~*gfp* mutants the VC neurons survive and express the *P*~*lin-11*~*gfp* reporter, suggesting that *lin-39* acts upstream of or parallel to *egl-1*. We performed similar experiments with *ceh-20* mutants (Fig. 3). Mutants carrying the weak *ay9* allele of *ceh-20* express the reporter in fewer cells in the midbody, consistent with programmed cell death of many of the VC neurons in these mutants. The VC neurons survive and express the *P*~*lin-11*~*gfp* reporter in *ceh-20*(**ay9**); *egl-1*(**n1084n3082**); *P*~*lin-11*~*gfp* mutants, but expression of the reporter was weak in some VC neurons, suggesting *ceh-20* may determine other aspects of VC identity in addition to being required for their survival. This suggestion is supported by the phenotype of mutants carrying the strong *ay42* allele of *ceh-20*. In *ceh-20*(**ay42**); *egl-1*(**n1084n3082**); *P*~*lin-11*~*gfp* mutants the VC neurons survive but do not express *P*~*lin-11*~*gfp* (Fig. 3). Expression of *P*~*lin-11*~*gfp* in *lin-39* null alleles but not in *ceh-20* mutants also suggests that *ceh-20* has *lin-39*-independent functions. These data are consistent with the model that *lin-39* and *ceh-20* act through *egl-1* to prevent programmed cell death of the VC neurons.

**A CEH-20/MAB-5 complex directly regulates egl-1 expression in P11.aaap**

A complex between CEH-20 and a Hox protein could regulate programmed cell death through direct regulation of *egl-1* transcription or indirectly through other cell fate determinants. We developed a rescue assay to define the *egl-1* genomic sequences required to restore a normal pattern of programmed cell death in the ventral nerve cord of *egl-1* mutants, and used this assay to examine candidate elements regulated by a CEH-20/Hox complex. A 7.6 kb genomic fragment of wild-type *egl-1* genomic DNA fully rescued programmed cell death in the ventral nerve cord of *egl-1*(**n1084n3082**) mutants (Fig. 4; data not shown). We compared *egl-1* genomic sequences between *C. elegans* and the related nematode *C. briggsae* to identify evolutionarily conserved sequences identical to the TGATNNAT consensus sequence
bound by Exd/Hox complexes. In this site, the 5′ half mediates binding by the PBC co-factor and the 3′ half mediates Hox binding (Chan and Mann, 1996; Mann and Affolter, 1998). Four such matches were identified (Fig. 4). Transgenic animals carrying an egl-1 genomic construct in which all four sites had been mutated from TGATNNAT to TCCATGGT had defects in programmed cell death in the ventral nerve cord (Fig. 4). Specifically, one cell in the P11 lineage survived in virtually all animals (average of 7.4 cells); two VC neurons (VC4 and VC5) are often obscured by vulval and sex muscle expression, and are not scored descendants (Cameron et al., 2002). VC and VC-like neurons undergo programmed cell death in lin-39 mutants (average of 9.0 cells). In lin-39 mutants, the P cell descendants migrate abnormally far forwards (Clark et al., 1993). (D, F) Many VC neurons die in ceh-20(ay9) mutants. In ceh-20(ay9), egl-1; P_{lin-11}gfp mutants, the VC and VC-like neurons survive and express P_{lin-11}gfp but the fluorescence is of variable brightness, especially in the anterior nerve cord (average of 7.4 cells). (G) In ceh-20(ay42), egl-1; P_{lin-11}gfp mutants, the VC and VC-like neurons survive but do not express P_{lin-11}gfp (average of 0 cells). Direct observation of cell lineages in the ceh-20(ay42), egl-1; P_{lin-11}gfp mutant confirmed that the VC neurons did not undergo programmed cell death. Arrowheads indicate nuclei of VC and VC-like neurons.

Electrophoretic mobility shift assays with epitope-tagged MAB-5 and CEH-20 proteins generated by coupled transcription and translation in vitro demonstrated specific binding by a CEH-20/MAB-5 protein complex to an oligonucleotide containing the site at +5995 of egl-1, and little binding by MAB-5 or CEH-20 alone (Fig. 5). Addition of antibody recognizing the epitope-tagged CEH-20 or MAB-5 altered mobility of the binding complex, consistent with binding of the oligonucleotide in vitro by a CEH-20/MAB-5 complex. Oligonucleotides with the TCCATGGT mutation or specific mutations of the individual half sites competed poorly for binding by the CEH-20/MAB-5 complex, consistent with these mutations disrupting function of the site in vivo.

**ceh-20 is expressed in P(11,12).aaap and many other cells**

To examine in which cells the ceh-20 gene is expressed, and specifically to test whether ceh-20 is expressed in P11.aaap where CEH-20 could interact with MAB-5 to regulate egl-1, we generated a rescuing cfp reporter construct. We generated transgenic animals that expressed a full-length CEH-20 protein with a fusion of CFP to the C terminus of the protein. Introduction of this construct into ceh-20(ay42) mutants rescued the egg-laying defect (data not shown). We introduced this construct into ced-3 mutants, in which P11.aaap and the other cells that undergo programmed cell death in the ventral nerve cord survive, and examined expression of the reporter construct. Consistent with a recent report of the expression pattern of a similar construct (Yang et al., 2005), we identified broad expression in many nuclei, including most ventral nerve cord neurons. We specifically identified expression in P11.aaap, which undergoes programmed cell death in a ceh-20-dependent fashion (Fig. 6). To address the possibility that ceh-20 is required for expression of mab-5, we examined expression of a P_{mab-5}.gfp reporter (Cowing and Kenyon, 1996) in ceh-20(ay42) mutants and identified no significant difference (Fig. 6), suggesting that ceh-20 is not required for expression of mab-5 in the P11 lineage. However, as ceh-20(ay42) is a strong loss of function but not null allele, this does not rule out regulation of Hox genes by ceh-20.

**egl-1 is regulated differently in P11.aaap and P12.aaap**

To determine precisely which cells are affected by mutation of the site at +5995, we followed P11 and P12 cell lineages in transgenic animals carrying the TCCATGGT mutation at position +5995 of an integrated egl-1 transgene (Fig. 7). In six out of seven animals, mutation of the site resulted in survival of P11.aaap, which survives in ceh-20 and mab-5 mutants. By contrast, in seven of seven animals P12.aaap, which survives in ceh-20 and mab-5 mutants, underwent programmed cell death. In three out of seven animals, we observed survival of P12.pp, a cell that in wild-type animals undergoes programmed cell death (Sulston and Horvitz, 1977). MAB-5 protein is present in P11.aaap when the cell is generated (Salser et al., 1993), consistent with binding by a CEH-20/MAB-5 complex to the site at +5995 and direct activation of egl-1 transcription in this cell. By contrast, in P12.aaap, MAB-5 is likely to act indirectly, as MAB-5 protein is undetectable after the first division in this lineage (Salser et al., 1993), 4 hours prior to the programmed cell death of P12.aaap. Survival of some P12.pp cells in animals with a mutation in the site at +5995 suggests that this site may mediate activation of egl-1 transcription to induce death of this cell. As P12.pp cell death occurs normally in mab-5 and ceh-20 mutants, perhaps a more posterior Hox gene and Hox co-factor [such as EGL-5 and the MEIS homolog UNC-62 (Van Auken et al., 2002)] act upon this site.
Fig. 4. An evolutionarily conserved site in egl-1 is required for programmed cell death of specific cells in the P11 and P12 lineages. (A) Light-gray boxes in the egl-1 genes of C. briggsae and C. elegans indicate regions with evolutionarily conserved sequences. The dark-gray boxes indicate the egl-1 open reading frame. Numbered asterisks indicate the locations of four evolutionarily conserved matches to the TGATNNAT Hox/Hox co-factor consensus. F23B12.1 encodes a predicted phosphatase that is not present in the C. briggsae (or C. remanei) egl-1 region. (B) C. elegans genomic DNA sequence is shown flanked by nucleotide positions relative to the egl-1 ATG. The positions of candidate binding sites are indicated. Nucleotides conserved in C. briggsae are indicated by black boxes. (C) Site 1 at position +5995 from C. elegans is shown. Mutated nucleotides are underlined. (D) The percentage of transgenic animals with the indicated number of corpses among the descendants of specific P cells. The diameters of the spots are proportional to the percentage of animals with the indicated number of corpses. Transgenic animals were constructed by biolistic transformation (Praitis et al., 2001) of ced-1(e1735); unc-119(ed3); egl-1(n1084n3082) mutants with the 7.6 kb genomic DNA of C. elegans egl-1 (see Materials and methods). Wild-type (WT) indicates introduction of wild-type genomic DNA. In general, 15 animals were scored for each independently derived transgenic line and the data were pooled (11 independent transgenic lines for the wild-type construct; 13 transgenic lines for the Site 1 NcoI construct; and six transgenic lines for the others). The F23B12.1 phosphatase was not required for the effects on programmed cell deaths of transgenic animals, and mutations affecting sites 2, 3 and 4 did not alter the pattern of programmed cell deaths in the ventral nerve cord (see Fig. S1 in the supplementary material). Deletion of the 470 nucleotide evolutionarily conserved region, including Site 1 (sequences 3’ of an XhoI site), resulted in a phenotype like that of mutations in Site 1. (E) DIC (a,c) and epifluorescence (b,d) images of some of the P11.a descendants of transgenic egl-1(n1084n3082) mutants carrying either a (a,b) wild-type Ppyl::histone:gfp reporter or a (c,d) mutant reporter in which Site 1 was changed to an NcoI site. Thirty out of 30 transgenic animals with a wild-type reporter expressed gfp in P11.aaap, and 29 of 30 expressed gfp in P11.aap. By contrast, of 90 descendants of three independent transgenic lines with a Site1 NcoI mutant reporter, only 11 expressed gfp in P11.aaap, while 83 out of 90 expressed gfp in P11.aap. P11.aap undergoes programmed cell death in wild-type animals and in mab-5 and ceh-20 mutants.
DISCUSSION

The Hox gene mab-5 is essential for programmed cell death of two lineally related cells in the P11 and P12 cell lineages. Based on the following six observations, we propose that a CEH-20/MAB-5 complex directly activates egl-1 transcription in P11.aaap to initiate programmed cell death. First, egl-1 is specifically transcribed in P11.aaap and is essential for the death of this cell. Second, mutations affecting ceh-20 or mab-5 result in a failure to transcribe egl-1 and survival of P(11,12).aaap. ceh-20 most probably acts through egl-1 to control programmed cell death of the VC neurons, and it seems likely that ceh-20 also acts through egl-1 in P(11,12).aaap. Third, mutations affecting an evolutionarily conserved regulatory sequence in egl-1 result specifically in a failure to transcribe egl-1 in P11.aaap and in survival of this cell. Fourth, this sequence includes a consensus Hox/Pbx site that binds a CEH-20/MAB-5 complex in vitro. Fifth, mutations that disrupt egl-1 function in vivo disrupt binding by CEH-20/MAB-5 in vitro. Sixth, MAB-5 and CEH-20 proteins are both present in P11.aaap.

Despite the similar patterns of cell division and cell fates in P11, P12 and their descendants, different mechanisms determine these lineages. In first larval stage animals, the P11 and P12 blast cells migrate into the ventral nerve cord from lateral positions, and laser ablation studies indicate that both cells are initially each capable of adopting the P12 fate (Sulston and White, 1980). Multiple intercellular signaling pathways, including EGF/EGFR-like (LIN-3/LET-23) and Wnt/Wnt receptor (LIN-44/LIN-17) pathways specify the P12 fate, in part by acting through the Hox protein egl-5 (Jiang and Sternberg, 1998). egl-5 is a homolog of Abd-B (Aboobaker and Blaxter, 2003; Chisholm, 1991; Wang et al., 1993). In egl-5-null mutants P12 is transformed to the P11 fate (Chisholm, 1991), and egl-5 represses expression of mab-5 in the P12 lineage after the first division (Salser et al., 1993). Less is known about how
programmed cell death. In this capacity, *egl-1* acts as a realizator gene (Garcia-Bellido, 1977) regulated by *mab-5* and *ceh-20* to effect morphogenesis, in this case by deleting a single cell from the developing animal. Previous target genes directly regulated by Hox proteins in *C. elegans* include only transcription factors (Koh et al., 2002; Liu and Fire, 2000). Identification of *egl-1* as a realizator gene activated by a Hox co-factor/Hox complex to induce programmed cell death in *C. elegans* supports the suggestion that non-homeotic targets of Hox proteins are common and evolutionarily ancient (Hombria and Lovegrove, 2003).

Mutations in the Hox gene *lin-39* also result in defects in programmed cell death; specifically, the six VC neurons of the midregion of the ventral nerve cord require *lin-39* for survival. We find that *ceh-20* is also required for survival of the VCs. Our data also suggest that *ceh-20* may determine one aspect of VC identity, expression of *lin-11*, through a mechanism that is *lin-39* independent. This suggestion is consistent with *lin-39*-independent functions for *ceh-20* in vulval development and neuronal migration (Yang et al., 2005). The mechanism through which *lin-39* and *ceh-20* regulate VC survival is not clear at present. Analogous to P11.aaap, a LIN-39/CEH-20 complex could directly repress transcription of *egl-1* in the VC neurons to ensure survival of the VC neurons. To confirm this model, regulatory sites in *egl-1* through which a LIN-39/CEH-20 complex acts must be identified. An alternative model is that LIN-39 and CEH-20 regulate *egl-1* indirectly, as MAB-5 apparently does in P12.aaap.

In *Drosophila*, the Hox genes *deformed* and *abdominal-B* activate transcription of *reaper* to induce programmed cell death and establish segment boundaries (Lohmann et al., 2002). *Reaper* and other functionally related genes initiate programmed cell death in *Drosophila* primarily by inhibiting the action of DIAPI1, a RING domain-containing protein that ubiquitinates the caspase DRONC and promotes its degradation (Ditzel et al., 2003; Goyal et al., 2000; Wang et al., 1999; Wilson et al., 2002). In mammals, developmental control of apoptosis is mediated in many cases by Bcl2 family members, particularly BH3 domain-encoding genes that are regulated in response to diverse stimuli (Puthalakath and Strasser, 2002). Our demonstration here of direct regulation of the BH3 domain-encoding gene *egl-1* by a Hox co-factor/Hox protein complex to initiate programmed cell death in *C. elegans* suggests the hypothesis that mammalian BH3 domain-encoding genes may be similarly regulated by Hox co-factor/Hox complexes as part of normal development of cells and tissues.

Previously, two pathways have been identified that directly regulate *egl-1* and programmed cell death of specific cells of *C. elegans*: both pathways contain genes whose human homologs are oncogenes (Conradt and Horvitz, 1999; Metzstein et al., 1996; Metzstein and Horvitz, 1999; Thellmann et al., 2003). Mutations affecting a mammalian homolog of *ces-2*, hepatic leukemia factor (HLF), may contribute to oncogenesis by preventing programmed cell death of malignant cells through an evolutionarily conserved mechanism. HLF is altered by the rare t(17;19) translocation in children with acute lymphoblastic leukemia (Inaba et al., 1992). The E2A-HLF fusion protein generated by the translocation inhibits programmed cell death of malignant precursor B lymphoblasts (Inaba et al., 1996). Based upon the genetic pathway established in *C. elegans* in which CES-2 acted through the Snail family member CES-1 to regulate programmed cell death, a human homolog of CES-1, SLUG, was identified and shown to mediate the actions of the fusion protein in preventing cell death of the malignant cells (Inukai et al., 1999).
We report here that the third pathway that directly regulates egl-1 also contains a human oncogene. A human homolog of ceh-20 is Pbx1, an oncogene initially identified at the t(1;19) breakpoint in children with acute lymphoblastic leukemia (Kamps et al., 1990; Nourse et al., 1990), the most common form of cancer in children. How mutations of Pbx1 promote leukemogenesis is not yet known. Some egl-1 homologs act during normal hematopoiesis to prevent the development of hematopoietic malignancy. For example, Bid-deficient mice develop a myeloproliferative disease that progresses to leukemia in many mice (Zinkel et al., 2003), and Bad-deficient mice develop diffuse large B cell lymphoma (Ranger et al., 2003). Hox genes have many well described functions during normal hematopoiesis and are frequently affected by chromosomal translocations in hematopoietic cancers (Grier et al., 2005). How expression of the BH3 domain-encoding genes is regulated during hematopoietic development is not yet clear, but direct regulation by Hox cofactor/Hox complexes of BH3 gene function to promote or prevent programmed cell death is an intriguing possibility.

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Supplementary material

Supplementary material for this article is available at http://dev.biologists.org/cgi/content/full/133/4/641/DC1

References


transcriptional and post-translational control of the pro-apoptotic activity of BH3-only proteins. Cell Death Differ. 9, 505-512.


