POP-1 controls axis formation during early gonadogenesis in C. elegans

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SUMMARY

The shape and polarity of the C. elegans gonad is defined during early gonadogenesis by two somatic gonadal precursor cells, Z1 and Z4, and their descendants. Z1 and Z4 divide asymmetrically to establish the proximal-distal axes of the gonad and to generate regulatory leader cells that control organ shape. In this paper, we report that pop-1, the C. elegans TCF/LEF-1 transcription factor, controls the first Z1/Z4 asymmetric division and hence controls proximal-distal axis formation. We have identified two pop-1(Sys) alleles (for symmetrical sisters) that render the Z1/Z4 divisions symmetrical. The pop-1(q645) allele is fully penetrant for the Sys gonadogenesis defect in hermaphrodites, but affects male gonads weakly; pop-1(q645) alters a conserved amino acid in the β-catenin binding domain. The pop-1(q624) allele is weakly penetrant for multiple defects and appears to be a partial loss-of-function mutation; pop-1(q624) alters a conserved amino acid in the HMG-box DNA binding domain. Zygotic pop-1(RNAi) confirms the role of pop-1 in Z1/Z4 asymmetry and reveals additional roles of pop-1, including one in leader cell migration. Two other Wnt pathway regulators, wrm-1 and lit-1, have the same effect as pop-1 on Z1/Z4 asymmetry. Therefore, wrm-1 and lit-1 are required for pop-1 function, rather than opposing it as observed in the early embryo. We conclude that POP-1 controls the Z1/Z4 asymmetric division and thereby establishes the proximal-distal axes of the gonad. This control over proximal-distal polarity extends our view of Wnt signaling in C. elegans, which had previously been known to control anterior-posterior polarities.

Key words: POP-1, C. elegans, Gonadogenesis, Axis formation, Wnt signaling

INTRODUCTION

Early steps in organogenesis include the specification of organ precursor cells, formation of an organ primordium, and establishment of organ polarity. We have begun to analyze early organogenesis in the nematode C. elegans, where its development can be analyzed in living animals at the level of individual cells. Our focus has been development of the gonad, which, like many organs, consists of an epithelial tube. The C. elegans gonad is a symmetrical organ in hermaphrodites and an asymmetrical one in males. Although a common genetic program underlies gonadogenesis in the two sexes (e.g. Blelloch et al., 1999; Friedman et al., 2000; Greenwald et al., 1983), early events must be controlled in a sex-specific manner to generate gonads with distinct polarity. More generally, this problem can be viewed as a paradigm for how developmental regulators can be modified to create distinct structures, a fundamental problem in evolutionary biology.

Gonadogenesis has been described in detail at the cellular level for both sexes [reviewed by Hubbard and Greenstein (Hubbard and Greenstein, 2000)]. The gonadal primordium contains two somatic gonadal precursor cells, Z1 and Z4 (Fig. 1A), which flank two germline precursor cells, Z2 and Z3 (not shown in Fig. 1). The first division of Z1 and Z4 establishes the proximal-distal (PD) axes of the organ. The hermaphrodite gonad will develop two ovo-testes, each with a PD axis; the male gonad will have a single testis, and therefore a single PD axis (Hirsh et al., 1976; Kimble and Hirsh, 1979). These PD axes are determined by the daughters of Z1 and Z4: after this first division the daughters with distal fates reside at the poles and the daughters with proximal fates are located centrally in both sexes (Fig. 1B). This arrangement persists in hermaphrodites throughout gonadogenesis. In males, however, the two proximal daughters migrate anteriorly and the anterior distal daughter is displaced posteriorly (Fig. 1C, left). The resultant structure (Fig. 1C, right) places the two proximal daughters at the anterior and the two distal daughters at the posterior end, transforming the symmetrical structure with two opposing PD axes into an asymmetrical structure with a single PD axis. In this way, the developing gonads acquire sex-specific polarities after a single division of Z1 and Z4.

In addition to establishment of organ polarity, other key events occur during early gonadogenesis that are crucial for morphogenesis. First, cells are generated that organize the developing gonad. Gonad shape is controlled by ‘leader cells’, which reside at the growing tips and govern elongation (Kimble and White, 1981) (Fig. 1D-G, red). In hermaphrodites, leader cells derive from the Z1/Z4 distal daughters, and are called distal tip cells (DTC) (Fig. 1D). In males, by contrast, the Z1/Z4 proximal daughters generate cells with leader...
potential, but lateral signaling directs one to differentiate as a leader cell, called a linker cell (LC), and the other to become a vas deferens (VD) precursor cell (Kimble, 1981) (Fig. 1E). Therefore, the number and position of leader cells is controlled by the asymmetric allocation of leader potential at the Z1/Z4 division in both sexes and lateral signaling in males.

In addition to specification of leader cells, two other regulatory functions are assigned early in gonadogenesis. In both sexes, the Z1/Z4 distal daughters (or granddaughters) signal the germline to proliferate (Kimble and White, 1981). In hermaphrodites, the germline proliferation and leader functions reside in the same cell (the DTC), whereas in males, they are allocated to separate cells: germline control in the DTCs and leader function in the linker cell (LC). Another regulatory cell specified during early gonadogenesis is the anchor cell (AC), which is specific to hermaphrodites and arises from the proximal Z1/Z4 daughters (Fig. 1D). The two cells competent to become the AC use lateral signaling (arrows, Fig. 1D) to make one AC and one ventral uterine (VU) precursor cell (Kimble, 1981). The AC induces vulval development in the ventral hypodermis (Kimble, 1981) and also induces nearby uterine precursors to take on the π cell fate (Newman et al., 1995).

Another key event, which completes early gonadogenesis, is formation of a ‘somatic primordium’: the blast cells in this primordium generate the somatic gonadal structures of the adult (Kimble and Hirsh, 1979). In hermaphrodites, all somatic gonadal cells, except the DTCs, migrate centrally and coalesce to create a hermaphrodite-specific somatic gonadal primordium (SPm) during the late L2 and early L3 stage (Fig. 1D). In males, all somatic gonadal precursor cells, except the DTCs, cluster anteriorly to form the male-specific somatic gonadal primordium (SPh) (Fig. 1E). These sex-specific somatic primordia (SP) prefigure the shape and pattern of the adult somatic gonadal structures.

Several genes are critical for early gonadogenesis [reviewed by Hubbard and Greenstein (Hubbard and Greenstein, 2000)]. Of particular importance for this work are lin-17 (Sternberg and Horvitz, 1988) and sys-1 (Miskowski et al., 2001). Both lin-17 and sys-1 affect the asymmetric division of Z1 and Z4. In lin-17 nonsense mutants and sys-1 strong loss-of-function mutants, Z1 and Z4 can divide symmetrically and generate two daughters that adopt the same, proximal fate (Fig. 1F,G). This is the Sys phenotype, for ‘symmetrical sisters’ (Miskowski et al., 2001). The lin-17 gene encodes a frizzled-like receptor (Sawa et al., 1996), implicating Wnt signaling in control of Z1/Z4 asymmetric divisions. The sys-1 gene encodes a novel protein, providing no additional clue to biochemical function (J. Miskowski, A. Kidd and J. K., unpublished). Although the sys-1 and lin-17 mutant phenotypes are similar, they are not identical (Miskowski et al., 2001).
also results in the same phenotype as loss of have typical Sys gonadal defects. We find that animals the Wnt signaling pathway and components of a Map kinase pathway that regulate POP-1 function. The phenotypes of these two alleles are both missense mutations, one in the β-catenin binding domain and one in the HMG box. The two alleles are distinct, both from each other and from those of pop-1(RNAi) progeny. To explore the pathway controlling Z1/Z4 asymmetry, we analyzed components of the canonical Wnt signaling pathway and components of a Map kinase pathway that regulate POP-1 function. We find that animals lacking either the β-catenin homologue wrm-1 or the nemo-like kinase (NLK) homologue lit-1 have typical Sys gonadal defects. Similarly, loss of lit-1 in a post-embryonic cell, called the T cell, also results in the same phenotype as loss of pop-1 (Herman, 2001). These results contrast to what has been found in the C. elegans embryo and in vertebrates, where lit-1 opposes pop-1 function (Ishitani et al., 1999; Kaletta et al., 1997; Meneghini et al., 1999; Rocheleau et al., 1999).

**MATERIALS AND METHODS**

**Strains**

Animals were grown at 20°C unless otherwise noted. All strains were derivative of Bristol strain N2 (Brenner, 1974). The following mutations have been described previously (Hodgkin, 1997) and cited references. LGI: pop-1(z189), lin-44(n1792), mom-4(or39) (Thorpe et al., 1997), mom-5(or57) (Thorpe et al., 1997), fog-1(q487), unc-11(e47), mec-2(q245), mec-8(e398), lin-17(sy277) (Sawa et al., 1996), tdf3, tdf4; LGIII: unc-32(e189), lin-12(n137 gf,x n720f), lit-1(t1512) (Kaletta et al., 1997), lit-1(t1534) (Kaletta et al., 1997), lit-1(or131) (Meneghini et al., 1999); LGIV: egl-20(n585), dce-1(ne219) (Tabara et al., 1999); LGV: mom-2(or42) (Thorpe et al., 1997); LGX: bar-1(ga80) (Eisenman and Kim, 2000), mom-1(or10), hT2(qs48) was used as a dominant green balancer chromosome. q5b48 is an insertion of cex9747 (contains pex-10::GFP, myo-2::GFP, and a gut enhancer driving GFP) onto hT2. In addition, the following markers were used: q5s19 and q5s6 are agg-2::GFP insertions (Blelloch et al., 1999), and syIs50 is a cdh-3::GFP insertion (Pettit et al., 1996).

**Isolation and genetic characterization of sys-2 mutations**

Two pop-1 alleles were isolated in an F2 screen following mutagenesis with ethyl methane sulfonate (EMS). These two mutations failed to complement and mapped to the left arm of chromosome I between lin-17 and mec-2 by 3-factor and deficiency mapping. The deficiency tdf4 complemented pop-1(q645) and tdf3 failed to complement pop-1(q645). From pop-1mek-2 unc-11, 18/18 Unc non-Mek progeny carried pop-1(Sys). We used the deletion allele lin-17(sy277) as a molecular marker for mapping. From pop-1 unc-11/1 lin-17, 53/53 Unc non-Sys carried the lin-17 deletion. We also failed to separate pop-1(z189) from pop-1(q645); from z189/q645 unc-11, 46/46 Unc-non Sys were Mel.

pop-1(q624) is recessive: wild-type males were crossed into pop-1(q624) mec-8/hT2[qs48]; all cross-progeny were wild type (n=91). pop-1(q645) shows minor dominance: wild-type males were crossed into pop-1(q645) mec-8/hT2[qs48]; 1% of pop-1(q645)/+ cross progeny had one gonad arm (n=77). In addition, whole broods were scored from pop-1(q645)/+: two broods were scored at 25°C, and three at 20°C. At 25°C, 24% had no gonad arms, 2% had one gonad arm, and 72% had two gonad arms. At 20°C, 26% had no gonad arms and 73% had two gonad arms. At both temperatures about 1% of embryos were dead. Because pop-1(q624) can be L1 lethal, we scored total survivors from eggs laid during an 8 hour time period, rather than whole broods. From a heterozygous pop-1(q624)/+ parent, 6% arrested or died as L1, and from a homozygous pop-1(q624) parent 65% arrested or died as L1. Animals that did not arrest as L1 grew to adulthood; gonad arms were scored in survivors (Table 1). This scheme was also used to assay lethality for pop-1(q645)/Df3 and pop-1(RNAi). To assay lethality in pop-1(q624)/Df3, we crossed pop-1(q624)/hT2[qs48] females (feminized by fog-1(RNAi)) with Df3/hT2[qs48] males. Fewer than one pop-1(q624)/Df3 (non-green) survivor was seen per mother; gonad arms were scored in survivors (Table 1).

Molecular analysis

Exons of pop-1 were sequenced from q5s24 and q5s45 homozygotes. Template DNA for sequencing was made by amplifying pop-1 exons.
from homozygotes using Expand™ High Fidelity PCR System (Boehringer Mannheim). At least three independent PCR reactions were sequenced from each mutant, and two independent RT-PCR reactions were sequenced from pop-1(q645) mutants. Big-Dye Terminator Ready Reaction Mix was used for sequencing reactions (PE/Applied BioSystems). Reactions were run by the Blattner Lab sequencing service, Department of Genetics, UW-Madison. Protein alignments were made using PILEUP from GCG Wisconsin Package v.10 (Genetic Computer Group, Madison, WI).

RESULTS

In a screen for mutants defective in early gonadogenesis, we identified two mutations, sys-2(q624) and sys-2(q645), that defined the sys-2 locus (see Methods). Genetic mapping placed sys-2 near pop-1, and three-factor-mapping failed to separate sys-2 from pop-1 (see Methods). The only pop-1 mutation available at the time was pop-1(zu189), a maternal effect lethal allele that disrupts maternal, but not zygotic, pop-1 (Lin et al., 1995; Morse and Bass, 1999). Although pop-1(zu189)/sys-2 transheterozygotes were not Sys, the mutations might be allelic, if pop-1(zu189) only affected maternal functions and pop-1(q645) primarily affected zygotic functions. To determine whether pop-1 might indeed influence early gonadogenesis, we used RNA-mediated interference (RNAi). We circumvented the pop-1 maternal effect lethality by injecting double stranded pop-1 RNA into a rde-1 homozygote, which is defective in RNAi (Tabara et al., 1999), then mated with wild-type males to generate rde-1/+ cross-progeny, which are zygotically sensitive to RNAi. This technique has been dubbed ‘zygotic RNAi’ (Herman, 2001). The pop-1(RNAi); rde-1/+ cross-progeny had numerous problems, including typical Sys gonadal defects (see below). We therefore suspected that sys-2 was actually pop-1. To test this idea, we first attempted mutant rescue and found that the pop-1-bearing cosmid BF8 (Lin et al., 1995) rescued sys-2(q624) to fertility (see Materials and Methods). We next sequenced all pop-1 exons from sys-2(q624) and sys-2(q645) mutants and found a single nucleotide change in each (Fig. 2A). We conclude that sys-2 is allelic with pop-1, and refer to the locus as pop-1 henceforth.

The pop-1 gene encodes a protein related to the TCF/LEF-1 transcription factor (Lin et al., 1995). Like other TCF-related proteins, POP-1 contains a conserved N-terminal β-catenin binding domain and a more central HMG box that binds DNA [reviewed by Roose and Clevers (Roose and Clevers, 1999)] (Fig. 2A). The pop-1(q645) mutation carries a nucleotide substitution predicted to change an aspartic acid (D) to a glutamic acid (E) (Fig. 2B); this mutation resides within the pop-1 β-catenin binding domain and alters an amino acid conserved in all known TCF/LEF-1 proteins, including nematode, fly, and vertebrate homologues. The pop-1(q624) mutation possesses a nucleotide change in the region encoding the HMG box; the predicted amino acid change in this case also affects a conserved amino acid (Fig. 2C). Therefore, both pop-1(Sys) mutations alter critical, although distinct, portions of the protein.

Early gonadogenesis in pop-1(Sys) hermaphrodites

The pop-1(Sys) hermaphrodites exhibit typical Sys gonadal defects. First, whereas wild-type hermaphrodites have two DTCs (Fig. 3A), pop-1(q645) mutants have none (Fig. 3B, Table 1). Similarly, pop-1(q624) mutants can lack gonadal arms and DTCs (Table 1, not shown). Second, whereas wild-type hermaphrodites possess a single AC (Fig. 3D), pop-1(Sys) mutants often have two or sometimes 3 AC (Fig. 3E, Table 1). Third, whereas wild-type hermaphrodites assemble an SP (Fig. 3A), this structure is never seen in pop-1(q645) hermaphrodites. Instead, a ring of somatic gonadal cells surrounds the germline at the L2/L3 stage (Fig. 3B, arrowheads).

The presence of two ACs could be explained either by an aberrant lineage or a defect in lateral signaling. Normally, Z1 and Z4 each produces a cell with potential to become an AC, and one is selected for the AC fate by lateral signaling (Fig. 1D, see Introduction). Lateral signaling is mediated by the LIN-12/Notch signaling pathway, and in lin-12 mutants two ACs are observed (Greenwald et al., 1983; Seydoux and Greenwald, 1989). To test if pop-1(Sys) mutants are defective in lateral signaling, we examined pop-1(q645); lin-12(0) double mutants and found that they made from four to ten ACs (Table 1). If pop-1 controlled polarity of the Z1/Z4 division...
and not subsequent divisions, a maximum of four ACs would be predicted in \( pop-1(q645); lin-12(0) \) double mutants. However, the production of more than four ACs suggests that \( pop-1 \) functions at multiple points of the Z1/Z4 lineage. We conclude that lateral signaling is functional in \( pop-1(Sys) \) mutants and limits the number of ACs made.

We next examined the early Z1/Z4 lineage in \( pop-1(q645) \) hermaphrodites (Fig. 4). Normally, Z1 and Z4 generate daughters with different fates (Fig. 4A). However, in \( pop-1(q645) \) mutants, Z1 and Z4 appear to generate daughters with equivalent fates (Fig. 4B). Although some variability was seen (see legend to Fig. 4), all Z1/Z4 daughters could divide twice, a pattern normally restricted to proximal daughters. Furthermore, all four daughters could produce AC/VU cells, as shown by laser ablation and assaying vulva formation. When Z1.p and Z4.a were ablated in \( pop-1(q645) \) hermaphrodites, a vulva was nearly always formed (9/10); similarly, when Z1.a and Z4.p were ablated, a vulva was made (6/6). However, when Z1 and Z4 were ablated, no vulva was formed (5/5). Therefore, the \( pop-1(Sys) \) Z1/Z4 daughters are equivalent with respect to their pattern of cell divisions and generation of AC/VU cells.

### Early gonadogenesis in \( pop-1(Sys) \) males

Unlike \( pop-1(Sys) \) hermaphrodite gonads, \( pop-1(Sys) \) male gonads can develop normally, and these males can be fertile (see Materials and Methods). To examine \( pop-1(Sys) \) males at a cellular level, we scored the production of regulatory cells and SPm formation. In wild-type males, the distal Z1/Z4

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**Table 1. Defects in \( pop-1(Sys) \) hermaphrodites**

<table>
<thead>
<tr>
<th>Genotype*</th>
<th>% hermaphrodites with x number gonadal arms&lt;sup&gt;†&lt;/sup&gt;</th>
<th>% hermaphrodites with x number anchor cells&lt;sup&gt;‡&lt;/sup&gt;</th>
<th>L1 lethal&lt;sup&gt;§&lt;/sup&gt; % (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+/+</td>
<td>100 0 0 &gt;100 n</td>
<td>100 0 0 0 45</td>
<td>0 (&gt;100)</td>
</tr>
<tr>
<td>( pop-1(q645) )</td>
<td>0 0 100 158</td>
<td>14 70 16 0 44</td>
<td>0 (&gt;100)</td>
</tr>
<tr>
<td>( pop-1(q645)/Df3 )</td>
<td>0 0 100 79</td>
<td>0 0 0 nd</td>
<td>20 (24)</td>
</tr>
<tr>
<td>( pop-1(q645); lin-12(0) )</td>
<td>0 0 100 24</td>
<td>nd nd nd</td>
<td>nd</td>
</tr>
<tr>
<td>( pop-1(q624) )</td>
<td>28 45 26 117</td>
<td>nd nd nd</td>
<td>6 (144)**</td>
</tr>
<tr>
<td>( pop-1(q624)^†† )</td>
<td>44 42 17 125</td>
<td>72 28 0 36</td>
<td>65 (147) ≥90 (&gt;100)</td>
</tr>
<tr>
<td>( pop-1(q624)/Df3 )</td>
<td>0 0 100 26</td>
<td>nd nd nd</td>
<td>nd</td>
</tr>
<tr>
<td>( pop-1(q624)/pop-1(q645) )</td>
<td>0 6 94 79</td>
<td>nd nd nd</td>
<td>nd</td>
</tr>
<tr>
<td>( pop-1(RNAi) )</td>
<td>0 0 100 56</td>
<td>14 62 24 0 21</td>
<td>27 (165)</td>
</tr>
</tbody>
</table>

<sup>*Mutants are homozygotes derived from heterozygous mothers of genotype \( pop-1(Sys)/ hT2[ql848] \), except where noted.</sup>

<sup>†Gonadal arms scored by Nomarski optics.</sup>

<sup>‡Anchor cells scored using \( cdh-3::GFP \) marker.</sup>

<sup>§In experiments requiring crosses, both males and hermaphrodites were scored.</sup>

<sup>**Percent lethality from heterozygous mothers of genotype \( pop-1(q624)/ + \).</sup>

<sup>††\( pop-1(q624) \) homozygotes derived from \( pop-1(q624) \) homozygous mother.**
daughters become DTCs, which are tiny and express lag-2::GFP weakly (Fig. 5A,B). A functional assay for male DTCs is germline proliferation: in the absence of DTCs the germline has a germline proliferation defect (Glp) (Kimble and White, 1981). We found that most pop-1(Sys) males made a robust germline, indicating that at least one DTC was made (Table 2). The production of DTCs in pop-1(Sys) males was corroborated by lag-2::GFP (Table 2), an assay that permits direct visualization of DTCs, but suffers from faint staining and an apparent enhancement of the Glp phenotype by the transgene (Table 2). Nonetheless, we found that 50% of pop-1(Sys) males made two DTCs (not shown). The wild-type male linker cell expresses lag-2::GFP intensely (Fig. 5A,B) (Blelloch et al., 1999). Similarly, all pop-1(Sys) males had at least one, and pop-1(q645) males sometimes had two LCs (Table 2; Fig. 5C,D). Furthermore, SPm formation was grossly normal in all pop-1(q645) males, but ~30% contained extra cells (Fig. 5D) \((n=17)\). We conclude that pop-1(Sys) male gonads have typical Sys defects, but at low penetrance.

**pop-1(RNAi) gonadal defects**

Given that the pop-1(Sys) alleles are missense mutations, we next examined the effect of pop-1(RNAi) on gonadogenesis. For most genes, RNAi drastically reduces mRNA to specific genes and can mimic the null phenotype (Fire et al., 1998; Rocheleau et al., 1997). As described above, we bypassed the requirement for maternal pop-1 by using an RNAi-resistant, rde-1 mutant mother. We note that the zygotic pop-1(RNAi) phenotype may not be equivalent to the zygotic null phenotype, since we do not know how early during embryogenesis the wild-type copy of rde-1 confers sensitivity to RNAi. The zygotic pop-1(RNAi); rde-1/+ progeny showed typical Sys defects, but at low penetrance.

**Fig. 4.** Early lineage of Z1 or Z4 in wild-type and pop-1 defective animals. (A-D) Vertical lines represent cells; horizontal lines represent divisions. Z1/Z4 represents Z1 or Z4; left daughter is distal; right daughter is proximal. DTC, distal tip cell; AC/VU, anchor cell or ventral uterine precursor; LC/VD, linker cell or vas deferens precursor. Only cell divisions in L1 and L2 were observed. (A) Wild-type hermaphrodite. The distal daughter divides once and gives rise to a DTC; the proximal daughter divides twice and gives rise to an ACNU. (B) pop-1(q645). Two hermaphrodites were watched from hatching until L2 lethargus. Z1/Z4 distal daughters divided twice, in three out of four cases; no DTCs were made. (C) Wild-type male. The distal daughter does not divide and becomes a DTC; the proximal daughter divides twice and gives rise to an LC/VD. (D) pop-1(RNAi) male. Z1/Z4 distal daughters both migrated anteriorly and divided once, albeit later than their proximal sisters. Later divisions were not followed.

**Fig. 5.** Defects in pop-1(Sys) and pop-1(RNAi) male gonads. All animals carry qIs56[lag-2::GFP], which expresses brightly in the LC and weakly in DTCs and other somatic gonadal cells. LC, linker cell; SPm, somatic primordium of male; DTC, distal tip cell. Extents of SPm and germline are indicated by brackets. (A,B) Wild-type L2 male. Single LC leads migration of the single gonadal arm. The SPm resides directly behind the LC and follows its migration. Two DTCs are present, but only one is seen in this focal plane (arrowhead). (C,D) pop-1(q645) male in L2 lethargus or early L3. Two LCs are present. The SPm appears normal: the somatic gonadal cells cluster to the anterior and follow the migrating LC. Only one DTC is present (arrowhead). (E,F) pop-1(RNAi) L2 male. Gonad polarity and organization are normal: the SPm is established at the anterior directly behind the LC. However, no DTCs are present and the LC has not migrated. The lack of LC migration is accompanied by a widening of the developing gonad.
Table 2. Gonadogenesis defects in pop-1(Sys) males

<table>
<thead>
<tr>
<th>Genotype*</th>
<th>Glp1</th>
<th>No DTCs5</th>
<th>Extra LCs6</th>
</tr>
</thead>
<tbody>
<tr>
<td>+/-</td>
<td>0 &gt;100</td>
<td>nd</td>
<td>0 &gt;100</td>
</tr>
<tr>
<td>pop-1(q624)</td>
<td>4 102</td>
<td>nd</td>
<td>46 75</td>
</tr>
<tr>
<td>pop-1(q645)</td>
<td>5 105</td>
<td>nd</td>
<td>11 54</td>
</tr>
<tr>
<td>+/-; lag-2::GFP</td>
<td>0 43</td>
<td>0 43</td>
<td>0 43</td>
</tr>
<tr>
<td>pop-1(q624); lag-2::GFP</td>
<td>9 32</td>
<td>6 32</td>
<td>0 15</td>
</tr>
<tr>
<td>pop-1(q645); lag-2::GFP</td>
<td>15 58</td>
<td>17 58</td>
<td>21 39</td>
</tr>
<tr>
<td>pop-1(RNAi); lag-2::GFP</td>
<td>not scored7</td>
<td>95 44</td>
<td>33 24</td>
</tr>
</tbody>
</table>

*Mutants are homozygotes derived from heterozygous mothers of genotype pop-1(Sys);yIs2(qIs48).

Scored by Nomarski optics; Glp animals have small germline composed of only sperm.

Scored by GFP fluorescence; DTCs observed as faint staining cells at posterior.

When scored by Nomarski, extra LCs observed by morphology of LC; when scored by GFP fluorescence, extra LCs observed as intense staining with typical LC morphology.

Gonadal organization too poor to score germline fates.

<table>
<thead>
<tr>
<th>Allele</th>
<th>% Z1/Z4 defective*</th>
<th>% T cells defective†,‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>q624</td>
<td>51% (234)</td>
<td>22% (64)</td>
</tr>
<tr>
<td>q645</td>
<td>100% (316)</td>
<td>37% (118)</td>
</tr>
<tr>
<td>RNAi</td>
<td>100% (66)</td>
<td>97% (88)</td>
</tr>
</tbody>
</table>

To monitor a non-gonadal defect that depends on Wnt signaling (Herman et al., 1995; Sawa et al., 1996), we assayed T cell polarity in both pop-1(Sys) mutants and pop-1(RNAi) animals. In wild-type hermaphrodites, the posterior T cell daughters give rise to the phasmid socket cells and the anterior daughters give rise to primarily hypodermis (Sulston and Horvitz, 1977). In the absence of Wnt signaling components, both daughters generate hypodermis and no phasms are made (Herman, 2001; Herman and Horvitz, 1994; Herman et al., 1995). We therefore scored phasms in pop-1(Sys) mutants and pop-1(RNAi) animals using a dye-filling assay (Herman and Horvitz, 1994). In both pop-1(Sys) mutants, fewer than normal phasms were made, whereas in pop-1(RNAi) animals, almost none were found (Table 3). Therefore, both alleles affect T cell polarity in addition to Z1/Z4 polarity. Interestingly, the percentage of pop-1(Sys) mutants with T cell lineage defects was roughly equivalent to the percentage of pop-1(Sys) males with Z1/Z4 defects, both of which were substantially lower than the percentage of pop-1(Sys) hermaphrodites with Z1/Z4 defects (Table 3).

Genetic analysis of pop-1(Sys) mutants

The pop-1(q624) and pop-1(q645) mutants are similar in phenotype, but not identical. Furthermore, neither phenotype is equivalent to that of zygotic pop-1(RNAi). We therefore explored the nature of the pop-1(Sys) mutations by standard genetic tests. We first tested whether either pop-1(Sys) mutation might be null. When pop-1(q624) was placed over a DTC, its penetrance became considerably more severe, both with respect to the Sys gonadal defect and L1 lethality (Table 1). Therefore, pop-1(q624) is clearly not a null and is likely to be a partial loss-of-function mutation.

A similar simple conclusion could not be made for pop-1(q645). This allele is fully penetrant for the Sys gonadal defect, as is pop-1(q645);tdf3 (Table 1). However, in contrast to pop-1(q624);tdf3 animals, which never made gonadal arms, a few q645/q645 hermaphrodites did possess gonadal arms (Table 1), suggesting that pop-1(q645) is a strong loss-of-function allele with respect to DTC production, but not a null. Intriguingly, L1 lethality was not seen in pop-1(q645) mutants and was far less severe in pop-1(q645);tdf3 than pop-1(q645);tdf3 animals (Table 1). The full penetrance of pop-1(q645) with respect to hermaphrodite gonadogenesis contrasts sharply with its extremely weak effect on L1 viability. We speculate that the pop-1(q645) mutation may affect a regulatory region essential for hermaphrodite gonadogenesis, but not for most other pop-1 functions (see Discussion).

L1 lethality was observed among pop-1(q624) mutants...
defects. Therefore, LIN-17 is the only frizzled receptor known. However, 3% of animals mutant for the
summarizes our results. We detected no gonadogenesis defect and available mutants to look for Sys defects. Table 4
gonadogenesis in nematodes, we used a combination of RNAi other Wnt signaling components might be involved in early
The Wnt signaling and gonadogenesis (Lin et al., 1995).
product plays a role that is crucial for L1 survival in addition to its previously known role in controlling early embryogenesis (Lin et al., 1995).

We also tested two β-catenin homologues in the C. elegans genome. RNAi of bar-1, a β-catenin that binds the β-catenin binding domain of POP-1 (Korswagen et al., 2000; Natarajan et al., 2001), does not give a Sys phenotype; nor does a bar-1 null mutant. However, RNAi of wrm-1, a second β-catenin homologue that weakly binds full length POP-1 (Korswagen et al., 2000; Natarajan et al., 2001; Rocheleau et al., 1999), gave a 100% penetrant Sys phenotype in both males and hermaphrodites (Table 4). LIT-1 functions with WRM-1 to phosphorylate POP-1 and regulates POP-1 function and localization (Meneghini et al., 1999; Rocheleau et al., 1999).
We found that lit-1 mutants can exhibit a Sys phenotype in both sexes when grown at 25°C. Therefore, wrm-1 and lit-1 loss-of-function both exhibit the same phenotype as pop-1 loss-of-function in the gonad.

DISCUSSION

POP-1 controls axis formation during gonadogenesis

C. elegans POP-1 belongs to the TCF/LEF-1 family of transcription factors, which are controlled by Wnt signaling [reviewed by Wodarz and Nusse (Wodarz and Nusse, 1998)]. Previous studies implicated Wnt signaling in the control of anterior-posterior (AP) cell polarity in the embryonic EMS blastomere (Lin et al., 1995; Rocheleau et al., 1997; Thorpe et al., 1997) and AP cell polarity in the post-embryonic T blast cells (Herman, 2001; Herman et al., 1995; Sawá et al., 1996), together to establish anterior-posterior (AP) cell polarity in the embryonic center cells (Herman, 2001; Herman et al., 1995; Sawa et al., 1996; Sternberg and Horvitz, 1988), as well as in the control of AP migration of Q neuronal blastomere (Meneghini et al., 1999; Rocheleau et al., 1999; Whangbo et al., 2000; Kenyon, 1999). Therefore, Wnt signaling is utilized in both embryonic and zygotic development to distinguish anterior versus posterior identities. In this paper, we report that POP-1 is critical during gonadogenesis. Rather than establishing AP polarity, Wnt signaling sets up the PD axes of the gonad.

During normal gonadogenesis, POP-1 governs the asymmetric division of Z1 and Z4, and thereby controls the gonadal PD axes and the generation of regulatory cells essential for subsequent morphogenesis. In the absence of POP-1 function, Z1 and Z4 generate equivalent daughters that both assume a proximal fate. Hermaphrodite gonads lacking pop-1 lose their PD axes and fail to generate regulatory cells required for gonad elongation and germline proliferation. Male gonads lacking pop-1 also lose their PD axis – they have no cells with distal fates and therefore no distal end. However, the male gonad acquires an apparently normal polarity, which reflects the male-specific specification of an AP axis in this organ.

How might POP-1 govern Z1/Z4 asymmetry? We suggest two simple models (Fig. 6A), although they are not mutually exclusive and others certainly exist. Both models take advantage of the fact that Z1 and Z4 contact each other ventrally beneath the two germline precursor cells, Z2 and Z3 (F-H. Markussen, L. Mathies, Y. Li, and J. Kimble, unpublished). In the first model (Fig. 6A, left), a Wnt signal polarizes Z1 and Z4, which leads to enhanced POP-1 activity in the distal daughter. Polarization may result from an inhibitory signal in the underlying hypodermis or from a decreased access of the Wnt to proximal regions of Z1/Z4. In

Table 4. Wnt pathway components and regulators controlling Z1/Z4 asymmetry

<table>
<thead>
<tr>
<th>Wnt pathway component</th>
<th>Gene</th>
<th>Method*</th>
<th>Sys $\phi$†</th>
<th>Sys $\phi$‡</th>
</tr>
</thead>
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<tr>
<td>Porcupine</td>
<td>mom-1</td>
<td>mutant</td>
<td>+</td>
<td>—</td>
</tr>
<tr>
<td>Wnt signal</td>
<td>lin-44</td>
<td>RNAi, mutant</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>egf-20</td>
<td>RNAi, mutant</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>mom-2</td>
<td>RNAi, mutant</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>cwn-1</td>
<td>RNAi</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>cwn-2</td>
<td>RNAi</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Frizzled receptor</td>
<td>lin-17</td>
<td>RNAi, mutant</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>cfc-1</td>
<td>RNAi</td>
<td>—</td>
<td>—</td>
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<td>RNAi</td>
<td>+</td>
<td>+</td>
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<td>nemo-like kinase</td>
<td>lit-1</td>
<td>mutants</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>TGFB-activated kinase</td>
<td>mom-4</td>
<td>mutant</td>
<td>—</td>
<td>nd</td>
</tr>
</tbody>
</table>

*See Materials and Methods for specific alleles and RNAi.
†+, Sys hermaphrodites observed (DTCs assayed by arm elongation or $lag-2::GFP$; extra ACs scored using cdh-3::GFP or by DIC optics).
—, no Sys animals observed.
‡+, Sys males observed (DTCs assayed by germline proliferation; extra LCs scored using DIC optics or $lag-2::GFP$ expression). Typically, males were only scored in RNAi experiments.

derived from a heterozygous mother (6%, n=144), but was more frequent among pop-1(q624) mutants derived from a homozygous mother (65%, n=147). Therefore, maternal pop-1 product plays a role that is crucial for L1 survival in addition to its previously known role in controlling early embryogenesis (Lin et al., 1995).

Wnt signaling and gonadogenesis

The pop-1 gene encodes a key transcription factor acting at the end of the Wnt pathway in C. elegans [reviewed by Wodarz and Nusse (Wodarz and Nusse, 1998)]. To determine what other Wnt signaling components might be involved in early gonadogenesis in nematodes, we used a combination of RNAi and available mutants to look for Sys defects. Table 4 summarizes our results. We detected no gonadogenesis defect for any of the five known Wnt homologues, by using RNAi for each of the five, or by analyzing mutants of three of them, or by double and triple RNAi (see Materials and Methods). However, 3% of animals mutant for the porcupine homologue, mom-1, had only one gonadal arm (n=72). Therefore, a Wnt ligand may be involved in Z1/Z4 polarity. We next examined three frizzled receptor homologues (Table 4). Previous work showed that a lin-17 nonsense mutant has a low penetrance Sys phenotype (Sternberg and Horvitz, 1988). Using RNAi, we confirmed this effect. RNAi directed against either of the other two frizzled receptor homologues, mom-5 and cfc-1, did not yield Sys defects. In addition, mom-5 mutants do not show Sys defects. Therefore, LIN-17 is the only frizzled receptor known to function in the early gonadal lineage, and its role is not essential. In RNAi experiments, genes with known mutant phenotypes exhibited expected defects (for example, mom-2(RNAi) produced 100% dead eggs when wild-type animals were injected), suggesting that RNAi of these genes was working to some extent.

We also tested two β-catenin homologues in the C. elegans...
the second model (Fig. 6A, right), no Wnt signal is invoked. Instead, contact between Z1 and Z4 (or contact between Z1/Z4 and the hypodermitis) polarizes the cell (for example, excluding LIN-17 from the proximal region), which leads to enhanced POP-1 activity in the distal daughters.

Wnt signaling controls primary axis formation in vertebrates [reviewed by Sokol (Sokol, 1999)] and limb axis formation in vertebrates [reviewed by Johnson and Tabin (Johnson and Tabin, 1997)] and flies [reviewed by Serrano and O’Farrell (Serrano and O’Farrell, 1997)]. In C. elegans, POP-1 controls axis formation during early organogenesis by controlling a key cell polarity (this work). In vertebrate primary axis formation, Wnt signaling is restricted to a dorsal developmental field by opposing ventral signals, leading to dorsal-ventral (D-V) axis specification; similar processes control limb DV axis specification [see the following reviews (Johnson and Tabin, 1997; Serrano and O’Farrell, 1997; Sokol, 1999)].

Polarization of Z1 and Z4 in C. elegans gonad development may act in a similar fashion: the proximal-distal axis may be determined by restriction of Wnt signaling to the distal Z1 and Z4 daughter cells.

**Identification of two distinct pop-1(Sys) mutations**

Prior to this paper, only one pop-1 mutation had been reported. This allele, pop-1(zu189), is a transposon insertion into the pop-1 3’ untranslated region that abolishes maternal pop-1 mRNA, but leaves zygotic pop-1 mRNA intact (Lin et al., 1995; Morse and Bass, 1999). The pop-1(zu189) allele identifies a regulatory site for maternal pop-1 mRNA, but does not shed light on regulatory regions within POP-1 protein itself. In this paper, we report two pop-1(Sys) mutations that change the pop-1 coding region and have dramatic effects on gonadogenesis. Our characterization of these alleles as well as zygotic pop-1(RNAi) suggests that one, pop-1(q624), is a typical partial loss-of-function mutation and that the other, pop-1(q645), is unusual. The pop-1(q624) defects are found at low penetrance, are similar to those observed by pop-1(RNAi) (e.g. L1 lethality, Sys gonads, T cell defects), and become more penetrant when the allele is placed over a deficiency. This mutation alters a conserved amino acid in the HMG box DNA binding domain which is conserved specifically in TCF/LEF-1 type HMG proteins (Laudet et al., 1993), suggesting that the pop-1(q624) mutation may affect either recognition of the TCF/LEF-1 consensus sequence or DNA binding affinity, thereby lowering POP-1 activity.

Unlike the weak pop-1(q624) mutation, pop-1(q645) is fully penetrant for the Sys gonadal defect in hermaphrodites, but exhibits no L1 lethality. Therefore, pop-1(q645) alters a residue essential for hermaphrodite gonadogenesis, but not for other pop-1-dependent events. The pop-1(q645) mutation alters an aspartic acid to glutamic acid in the β-catenin binding domain. This amino acid is conserved in all TCF/LEF-1 homologues and, through analysis of vertebrate homologues, has been shown to be essential for β-catenin binding and for β-catenin and TCF/LEF-1 to activate transcription of target genes (Graham et al., 2000; Hsu et al., 1998; von Kries et al., 2000). Although two missense mutations affecting the β-catenin binding domain of the D. melanogaster TCF/LEF-1 homologue, Pan, have been isolated, neither of these two mutations affects residues conserved among all TCF/LEF-1 homologues (Brunner et al., 1997). As the only mutation isolated thus far in a developmental system that changes a highly conserved amino acid in the β-catenin binding domain, the pop-1(q645) missense mutation may shed new light on TCF/LEF-1 function during development. It is striking that the β-catenin homologue critical for Z1/Z4 asymmetry is WRM-1, which does not bind the POP-1 β-catenin binding domain (Korswagen et al., 2000; Natarajan et al., 2001; Rocheleau et al., 1999). We speculate that the POP-1 β-catenin binding site may interact with a regulator in Z1 and Z4 that differentially affects that tissue.

**Z1/Z4 asymmetry, POP-1 control and sexual dimorphism?**

Because pop-1(q645) mutant hermaphrodites are always sterile while mutant males can be fertile, we looked for sex-specific defects in pop-1(Sys) mutants and pop-1(RNAi) animals. We found that POP-1 controls Z1/Z4 asymmetry in both sexes. Unlike pop-1(RNAi), which has equivalent strong effects on both sexes, the two pop-1(Sys) mutations affect hermaphrodite gonadogenesis more strongly than male gonadogenesis (Table 3). This difference in the effect of pop-1 mutations may reflect a more stringent requirement for pop-1 activity in the hermaphrodite gonad, it may reflect a more stringent dependence of the hermaphrodite gonad on correctly establishing the PD axes, or it may reflect a sex-specific regulation of POP-1. If sex-specific regulation occurs, the unusual pop-1(q645) mutation may identify the POP-1 β-catenin binding domain as the site of that regulation.

PD axis specification is required for SP formation in hermaphrodites, but not in males. In pop-1(Sys) and pop-1(RNAi) hermaphrodites, SP formation is disrupted resulting in a disorganized organ and sterility. However, in pop-1(Sys) and pop-1(RNAi) males, early cell rearrangements
that establish the AP axis of the male gonad occur as normal, and overall organ polarity appears normal. Therefore, AP axis specification in the male gonad does not require proper specification of the PD axis.

**The POP-1 pathway controls Z1/Z4 asymmetry**

We surveyed Wnt signaling components and additional regulators of POP-1 for control of Z1/Z4 asymmetry and found that a decrease in either WRM-1, a β-catenin homologue, or LIT-1, a nemo-like kinase (NLK) homologue, led to Z1/Z4 defects similar to those of decreased POP-1 activity. Furthermore, previous work showed that the lin-17 receptor is involved, albeit with lower penetrance (Sawa et al., 1996; Sternberg and Horvitz, 1988). Surprisingly, we identified no Wnt signal as critical for Z1/Z4 polarity. This negative result may mean that a Wnt signal is not required, that the signal is encoded by redundant wnt genes, or that it is not sensitive to RNAs. At present, we cannot distinguish among these possibilities. Our models (Fig. 6A) leave open the possibility that a Wnt signal may exist.

Fig. 6B summarizes the pathway of POP-1 control in the gonad and compares that control to what has been observed in other C. elegans tissues. In Z1/Z4, WRM-1 and LIT-1 are both required for POP-1 activity. All three genes are required for the distal fate. By contrast, WRM-1 and LIT-1 antagonize POP-1 activity in the embryo (Kaletta et al., 1997; Meneghini et al., 1999; Rocheleau et al., 1999) and LIT-1, but not WRM-1, is involved in controlling T cell polarity (Herman, 2001; Rocheleau et al., 1999).

We envision two explanations for how WRM-1 (a β-catenin) and LIT-1 (NLK) may act to enhance POP-1 activity in the gonad. One simple explanation is that WRM-1 and LIT-1 may positively regulate POP-1; this idea is based on classical results that β-catenins are TCF co-activators [reviewed by Wodarz and Nusse (Wodarz and Nusse, 1998)], and that NLK is complexed with TCF and β-catenin (Ishitani et al., 1999). The WRM-1 β-catenin does not bind the POP-1 β-catenin binding domain per se, but weakly binds full length POP-1 (Korswagen et al., 2000; Natarajan et al., 2001; Rocheleau et al., 1999). Perhaps WRM-1 interacts with POP-1 in Z1/Z4 and serves there as a coactivator. Such a physical interaction might be stabilized by another binding protein, such as LIT-1, which is known to bind POP-1 (Natarajan et al., 2001; Rocheleau et al., 1999). A second possibility is that WRM-1 and LIT-1 negatively regulate POP-1, reducing its level to an active state; this rather counterintuitive model was proposed by Herman (Herman, 2001) to explain how POP-1 might be regulated in the T cells. If the Herman model holds true in Z1/Z4 as well, then WRM-1/LIT-1 may downregulate POP-1 in the distal daughters and thereby bring POP-1 to the appropriate level to drive distal fates. The first model predicts that POP-1 will be more abundant in the distal daughters, whereas the Herman model predicts POP-1 to be more abundant in the proximal daughters. Unfortunately, POP-1 antibodies currently available do not reliably stain the L1 gonad, although hypodermal and other tissues stain well (K. Siegfried, unpublished). We have therefore been unable to distinguish between these two models.

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