The neogenin/DCC homolog UNC-40 promotes BMP signaling via the RGM protein DRAG-1 in C. elegans

Chenxi Tian1*, Herong Shi1, Shan Xiong2, Fenghua Hu1,3, Wen-Cheng Xiong2 and Jun Liu1,‡

SUMMARY

The deleted in colorectal cancer (DCC) homolog neogenin functions in both netrin- and repulsive guidance molecule (RGM)-mediated axon guidance and in bone morphogenetic protein (BMP) signaling. How neogenin functions in mediating BMP signaling is not well understood. We show that the sole C. elegans DCC/neogenin homolog UNC-40 positively modulates a BMP-like pathway by functioning in the signal-receiving cells at the ligand/receptor level. This function of UNC-40 is independent of its role in netrin-mediated axon guidance, but requires its association with the RGM protein DRAG-1. We have identified the key residues in the extracellular domain of UNC-40 that are crucial for UNC-40–DRAG-1 interaction and UNC-40 function. Surprisingly, the extracellular domain of UNC-40 is sufficient to promote BMP signaling, in clear contrast to the requirement of its intracellular domain in mediating axon guidance. Mouse neogenin lacking the intracellular domain is also capable of mediating BMP signaling. These findings reveal an unexpected mode of action for neogenin regulation of BMP signaling.

KEY WORDS: BMP signaling, Neogenin, DCC, UNC-40, RGM, DRAG-1, Caenorhabditis elegans

INTRODUCTION

The development of multicellular organisms requires the proper spatial and temporal coordination of many intracellular and extracellular signals. Among the extracellular signals are the bone morphogenetic proteins (BMPs), which belong to the transforming growth factor-β (TGFβ) superfamily of ligands. BMPs regulate a variety of developmental processes (Wu and Hill, 2009). Malfunction of this pathway causes many somatic and hereditary disorders in humans, including skeletal abnormalities, cardiovascular diseases and cancer (Gordon and Blobe, 2008; Massagué, 2008; Cai et al., 2012). Activation of the canonical BMP pathway starts with the formation of the BMP ligand-type I-type II receptor ternary complex, which in turn leads to the phosphorylation of the receptor-regulated Smads (R-Smads). These activated R-Smads then complex with common-mediator Smads (co-Smads), enter the nucleus and complex with transcriptional co-factors to regulate downstream gene expression (Shi and Massagué, 2003).

Owing to the diverse functions of the BMP pathway, multiple factors act as modulators to ensure proper spatiotemporal control of BMP signaling (Balemans and Van Hul, 2002; Umulis et al., 2009; Huang and Chen, 2012; Ramel and Hill, 2012). The transmembrane protein neogenin is one such factor. Neogenin is a member of the deleted in colorectal cancer (DCC) family and serves as a receptor for the guidance cue netrin (Keino-Masu et al., 1996) and the repulsive guidance molecules (RGMs) (Cole et al., 2009; Huang and Chen, 2012; Rajagopalan et al., 2012). Activation of the canonical BMP pathway starts with the formation of the BMP ligand-type I-type II receptor ternary complex, which in turn leads to the phosphorylation of the receptor-regulated Smads (R-Smads). These activated R-Smads then complex with common-mediator Smads (co-Smads), enter the nucleus and complex with transcriptional co-factors to regulate downstream gene expression (Shi and Massagué, 2003).

Owing to the diverse functions of the BMP pathway, multiple factors act as modulators to ensure proper spatiotemporal control of BMP signaling (Balemans and Van Hul, 2002; Umulis et al., 2009; Huang and Chen, 2012; Ramel and Hill, 2012). The transmembrane protein neogenin is one such factor. Neogenin is a member of the deleted in colorectal cancer (DCC) family and serves as a receptor for the guidance cue netrin (Keino-Masu et al., 1996) and the repulsive guidance molecules (RGMs) (Cole et al., 2009; Rajagopalan et al., 2012). Activation of the canonical BMP pathway starts with the formation of the BMP ligand-type I-type II receptor ternary complex, which in turn leads to the phosphorylation of the receptor-regulated Smads (R-Smads). These activated R-Smads then complex with common-mediator Smads (co-Smads), enter the nucleus and complex with transcriptional co-factors to regulate downstream gene expression (Shi and Massagué, 2003).

Owing to the diverse functions of the BMP pathway, multiple factors act as modulators to ensure proper spatiotemporal control of BMP signaling (Balemans and Van Hul, 2002; Umulis et al., 2009; Huang and Chen, 2012; Ramel and Hill, 2012). The transmembrane protein neogenin is one such factor. Neogenin is a member of the deleted in colorectal cancer (DCC) family and serves as a receptor for the guidance cue netrin (Keino-Masu et al., 1996) and the repulsive guidance molecules (RGMs) (Cole et al., 2009; Huang and Chen, 2012; Rajagopalan et al., 2012). Activation of the canonical BMP pathway starts with the formation of the BMP ligand-type I-type II receptor ternary complex, which in turn leads to the phosphorylation of the receptor-regulated Smads (R-Smads). These activated R-Smads then complex with common-mediator Smads (co-Smads), enter the nucleus and complex with transcriptional co-factors to regulate downstream gene expression (Shi and Massagué, 2003).

Owing to the diverse functions of the BMP pathway, multiple factors act as modulators to ensure proper spatiotemporal control of BMP signaling (Balemans and Van Hul, 2002; Umulis et al., 2009; Huang and Chen, 2012; Ramel and Hill, 2012). The transmembrane protein neogenin is one such factor. Neogenin is a member of the deleted in colorectal cancer (DCC) family and serves as a receptor for the guidance cue netrin (Keino-Masu et al., 1996) and the repulsive guidance molecules (RGMs) (Cole et al., 2009; Huang and Chen, 2012; Rajagopalan et al., 2012). Activation of the canonical BMP pathway starts with the formation of the BMP ligand-type I-type II receptor ternary complex, which in turn leads to the phosphorylation of the receptor-regulated Smads (R-Smads). These activated R-Smads then complex with common-mediator Smads (co-Smads), enter the nucleus and complex with transcriptional co-factors to regulate downstream gene expression (Shi and Massagué, 2003).

Owing to the diverse functions of the BMP pathway, multiple factors act as modulators to ensure proper spatiotemporal control of BMP signaling (Balemans and Van Hul, 2002; Umulis et al., 2009; Huang and Chen, 2012; Ramel and Hill, 2012). The transmembrane protein neogenin is one such factor. Neogenin is a member of the deleted in colorectal cancer (DCC) family and serves as a receptor for the guidance cue netrin (Keino-Masu et al., 1996) and the repulsive guidance molecules (RGMs) (Cole et al., 2009; Huang and Chen, 2012; Rajagopalan et al., 2012). Activation of the canonical BMP pathway starts with the formation of the BMP ligand-type I-type II receptor ternary complex, which in turn leads to the phosphorylation of the receptor-regulated Smads (R-Smads). These activated R-Smads then complex with common-mediator Smads (co-Smads), enter the nucleus and complex with transcriptional co-factors to regulate downstream gene expression (Shi and Massagué, 2003).

Owing to the diverse functions of the BMP pathway, multiple factors act as modulators to ensure proper spatiotemporal control of BMP signaling (Balemans and Van Hul, 2002; Umulis et al., 2009; Huang and Chen, 2012; Ramel and Hill, 2012). The transmembrane protein neogenin is one such factor. Neogenin is a member of the deleted in colorectal cancer (DCC) family and serves as a receptor for the guidance cue netrin (Keino-Masu et al., 1996) and the repulsive guidance molecules (RGMs) (Cole et al., 2009; Huang and Chen, 2012; Rajagopalan et al., 2012). Activation of the canonical BMP pathway starts with the formation of the BMP ligand-type I-type II receptor ternary complex, which in turn leads to the phosphorylation of the receptor-regulated Smads (R-Smads). These activated R-Smads then complex with common-mediator Smads (co-Smads), enter the nucleus and complex with transcriptional co-factors to regulate downstream gene expression (Shi and Massagué, 2003).

Owing to the diverse functions of the BMP pathway, multiple factors act as modulators to ensure proper spatiotemporal control of BMP signaling (Balemans and Van Hul, 2002; Umulis et al., 2009; Huang and Chen, 2012; Ramel and Hill, 2012). The transmembrane protein neogenin is one such factor. Neogenin is a member of the deleted in colorectal cancer (DCC) family and serves as a receptor for the guidance cue netrin (Keino-Masu et al., 1996) and the repulsive guidance molecules (RGMs) (Cole et al., 2009; Huang and Chen, 2012; Rajagopalan et al., 2012). Activation of the canonical BMP pathway starts with the formation of the BMP ligand-type I-type II receptor ternary complex, which in turn leads to the phosphorylation of the receptor-regulated Smads (R-Smads). These activated R-Smads then complex with common-mediator Smads (co-Smads), enter the nucleus and complex with transcriptional co-factors to regulate downstream gene expression (Shi and Massagué, 2003).

Owing to the diverse functions of the BMP pathway, multiple factors act as modulators to ensure proper spatiotemporal control of BMP signaling (Balemans and Van Hul, 2002; Umulis et al., 2009; Huang and Chen, 2012; Ramel and Hill, 2012). The transmembrane protein neogenin is one such factor. Neogenin is a member of the deleted in colorectal cancer (DCC) family and serves as a receptor for the guidance cue netrin (Keino-Masu et al., 1996) and the repulsive guidance molecules (RGMs) (Cole et al., 2009; Huang and Chen, 2012; Rajagopalan et al., 2012). Activation of the canonical BMP pathway starts with the formation of the BMP ligand-type I-type II receptor ternary complex, which in turn leads to the phosphorylation of the receptor-regulated Smads (R-Smads). These activated R-Smads then complex with common-mediator Smads (co-Smads), enter the nucleus and complex with transcriptional co-factors to regulate downstream gene expression (Shi and Massagué, 2003).
derivative of pJKL849 (Tian et al., 2010) with sequences corresponding to the third intron of drag-1 deleted. MosSCI single-copy insertion lines were generated using the direct gonadal injection method following the protocol described (Frokjaer-Jensen et al., 2008). Primer pairs CXT310 (GCGG-GATCATTTCTTACTAG)/CXT226 (ACTGACGAATTCCTTGAATTGG-TAAATACCTCTT) and CXT312 (CAAGGACTTGATTTAAATTGGC)/ CXT311 (GGTATCTGATATTACAAATA) were used to verify the insertion in different transgenic lines.

Body size measurement
Hermaphrodite animals at the gravid adult stage were collected and treated with hypochlorite. The resulting embryos were allowed to hatch in M9 buffer at 16°C. Synchronized L1s were plated onto NGM plates and allowed to grow for 48 or 72 hours before they were washed off the plates, treated with 0.3% sodium azide, and mounted onto 2% agarose pads. Images of the worms were taken on a Leica DMRA2 compound microscope with a Hamamatsu Orca-ER camera using Openlab software (Improvision). To overcome the slow growth phenotype of certain mutant strains, animals whose vulva development was at the early Christmas tree stage were used for body size measurement in certain experiments. Subsequent statistical analyses were performed using Microsoft Excel.

RAD-SMAD reporter assay
Hermaphrodites carrying the RAD-SMAD reporter jlls2437 II (Tian et al., 2010) were treated with hypochlorite. The resulting embryos were allowed to hatch in M9 buffer at 16°C. Synchronized L1s were plated onto NGM plates and allowed to grow for 48 hours. The resulting L3 animals were anesthetized. Images of the hypodermal cells were taken at 40× magnification on a Leica DMRA2 compound microscope. Fluorescence intensity of the nuclear GFP and background was measured in pairs using the Openlab software. Five nuclei/background pairs were measured for each worm. A total of 40 worms was measured per genotype. The mean signal value of each worm was deduced by averaging nuclear signal minus background signal. Standard deviation was then calculated using Microsoft Excel.

Assays to evaluate the UNC phenotypes of unc-40 mutants
Synchronized L1s were plated onto NGM plates and allowed to grow for different lengths of time. Forty-eight hours post-plating, the AVM neuronal migration defect was determined by examining AVM axon projection using the mec-4::gfp (zds5) marker (Clark and Chiu, 2003). Animals that failed to project the AVM axon ventrally were considered abnormal (supplementary material Fig. S1). The movement defect was determined by visually inspecting the movement of animals 72 hours post-plating. The wild-type-like moving animals were given a score of 1 and the animals that rarely moved or moved in an extremely uncoordinated fashion upon stimulation were given a score of 4. The egg-laying defective (Egl) phenotype was determined at 100 hours post-plating by counting the number of animals that died as a ‘bag of worms’ due to defective egg laying.

Immunofluorescence staining
Animal fixation, immunostaining, microscopy and image analysis were performed as described previously (Tian et al., 2010). Guinea pig anti-F0Z1-1 (1:200) (Amin et al., 2007), mouse monoclonal anti-AJM-1 MH27 (1:100; Developmental Studies Hybridoma Bank, University of Iowa), rat anti-MLS-2 (1:200) (Jiang et al., 2005) and goat anti-GFP (1:1000; Rockland Immunchemicals) were used.

Cell culture and transient transfection
HEK293T cells (for co-immunoprecipitation experiments), HEK293 cells (for BMP assays) and primary skin fibroblasts were maintained in Dulbecco’s Modified Eagle Medium supplemented with 10% fetal calf serum and 100 units/ml penicillin G and streptomycin ( Gibco). HEK293 or HEK293T cells were transfected by the calcium phosphate method as described previously (Lee et al., 2010). Primary fibroblasts were plated at a density of 10⁶ cells per 10-cm culture dish and allowed to grow for 24-48 hours before transfection using Lipofectamine 2000 (Invitrogen). Forty-eight hours after transfection, cells were washed, serum starved overnight, and then treated with BMP2 (30 minutes for HEK293 cells and 60 minutes for fibroblasts). Cells were then subjected to western blot or luciferase assay analyses, respectively. Alternatively, cell media or cell lysates were collected for co-immunoprecipitation assays as described below.

Luciferase assay
Luciferase assay was carried out as described previously (Zhou et al., 2010). In brief, cells were washed with PBS and lysed in lysis buffer (Promega) for 20 minutes at room temperature. Then, 50 μl of lysate were used to determine relative luciferase activity (firefly luciferase activity divided by Renilla luciferase activity) using a dual luciferase assay system (Promega). The luciferase activity data are the average of two independent cell isolations, each performed in triplicate.

Co-immunoprecipitation assays
For proteins that were expressed as soluble proteins, including mutated and wild-type Myc-FNS5,6, DRAG-1 (mature domain)-FLAG, DRAG-1 (mature domain)-Myc and FLAG-DBL-1 (mature domain), cell media were collected 5 days after transfecting the corresponding protein-expressing plasmids. For the remaining proteins, including mutated and wild-type DRAG-1 (mature domain)-FLAG, Myc-SMA-6 and Myc-DAF-4, cell lysates were collected 48 hours post-transfection. Anti-cMyc-conjugated Sepharose beads (Sigma EzView; 8 μl beads per reaction) or anti-FLAG-conjugated Sepharose beads (Sigma M2 EzView; 6 μl per reaction) were first incubated with cell lysates or media containing the first protein for 4 hours at 4°C, then with cell lysates or media containing the second protein for 4 hours or overnight at 4°C. The beads were then subjected to five washes with lysis buffer (50 mM Tris pH 8.0, 150 mM NaCl, 1% Triton X-100), boiled in SDS sample buffer and run on 10% SDS-PAGE gels. Western blots were probed with mouse anti-FLAG (M2) or mouse anti-Myc (9E10) antibodies (Sigma-Aldrich).

RESULTS
Mutations in the C. elegans neogenin homolog unc-40 cause phenotypes resembling those of Smo/Mab pathway mutants
The C. elegans BMP-like Smo/Mab pathway regulates body size and male tail patterning (Savage-Dunn, 2005). Mutations in this pathway can also suppress the mesodermal M lineage phenotypes of smo-9(0) mutants (Foehr et al., 2006; Tian et al., 2010). Specifically, the two coelomocytes (CCs) derived from the dorsal M lineage (Fig. 1C) are missing in smo-9(0) mutants due to a dorsal-to-ventral fate transformation in the M lineage (Fig. 1A,D). These two CCs can be restored in double mutants between smo-9(0) and mutations in Smo/Mab pathway members (Fig. 1B,C). In a large-scale screen for mutations that could suppress the loss-of-M-derived CCs phenotype of smo-9(cc604) mutants (the mutagenesis screen will be described in a separate manuscript), we identified a recessive mutation jlls59 that exhibited a penetrance of 73.3% (n=195) of suppression of the smo-9(cc604) M lineage phenotype (SOSMLP) (Table 1). Genetic mapping, complementation test and sequencing showed that jlls59 is a nonsense mutation (Q628Stop, CAA to TAA) in the sole C. elegans neogenin and DCC homolog unc-40 (Table 1, Table 3A). A canonical unc-40 null allele, e1430 (Hedgecock et al., 1990), also suppressed the M lineage phenotype of smo-9(cc604) mutants (88.7%, n=150, Table 1). Both unc-40(jlls59) and unc-40(e1430) mutants also have a significantly smaller body size than wild-type worms at the same developmental stage (Table 1). Thus, unc-40 mutants exhibit phenotypes of Smo/Mab pathway mutants.

Mutations in the C. elegans netrin ortholog unc-6 and the netrin receptor gene unc-5 do not exhibit Smo/Mab pathway mutant phenotypes
UNC-40 has been well studied as a DCC ortholog that functions as a netrin receptor in both UNC-5-dependent and UNC-5-independent pathways to mediate axonal and cellular movement guidance (Hedgecock et al., 1990; Kennedy et al., 1994; Chan et al., 1996;
the suppression of the unc-6(ev400) and the small body size phenotype. Unlike pathway mutants suggest that UNC-40 functions at the ligand-receptor level to (Hedgecock et al., 1990). Thus, UNC-40 appears to play a role in unc-40 a ‘DUMPY’ phenotype for unc-5, but not phenotypes (Table 1). Interestingly, Hedgecock and colleagues noted modulating Sma/Mab signaling by examining the null mutants of investigated whether UNC-6/netrin and UNC-5 play a role in Colón-Ramos et al., 2007; Teichmann and Shen, 2011). We UNC-40/neogenin in BMP signaling N.A., not applicable.

Body length data shown here and in subsequent figures and tables were normalized over that of unc-40(e1430) mutants. Data are mean ± s.d. ***P<0.0001, unc-40(e1430) versus other mutants (Student’s t-test).

Table 1. Summary of body size and mesodermal phenotypes in unc-40, unc-5 and unc-6 null mutants

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Molecular lesions</th>
<th>Relative body length</th>
<th>SOSMLP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT</td>
<td></td>
<td>1.16±0.06*** (n=27)</td>
<td>N.A.</td>
</tr>
<tr>
<td>unc-40(e1430)</td>
<td>R157STOP (null)</td>
<td>1.00±0.04 (n=50)</td>
<td>88.7 (n=150)</td>
</tr>
<tr>
<td>unc-40(jj59)</td>
<td>Q62STOP (null)</td>
<td>0.99±0.06 (n=46)</td>
<td>73.3 (n=195)</td>
</tr>
<tr>
<td>unc-5(e53)</td>
<td>W283STOP (null)</td>
<td>1.14±0.05** (n=59)</td>
<td>1.7 (n=59)</td>
</tr>
<tr>
<td>unc-6(ev400)</td>
<td>Q78STOP (null)</td>
<td>1.14±0.06** (n=20)</td>
<td>0.5 (n=221)</td>
</tr>
</tbody>
</table>

UNC-40 is expressed and functions in the Sma/Mab signal-receiving cells

We next examined the expression pattern of an integrated UNC-40::GFP transgene that is functional in mediating axon guidance (Chan et al., 1996). This transgene rescued the small body size and SOSMLP phenotypes of unc-40(e1430) mutants (Table 3B, the...
To determine whether UNC-40 functions in the signal-receiving cells of the Sma/Mab pathway, we forced the expression of the unc-40 cDNA in hypodermal cells using both the elt-3 and rol-6 promoters (Kramer and Johnson, 1993; Gilleard et al., 1999) and in the M lineage using the hth-8 promoter (Harfe et al., 1998). Forced expression of unc-40 in hypodermal cells rescued the small body size phenotype (Table 2), and forced expression of unc-40 in the M lineage rescued the SOSMPL phenotype (SOSMPL down to 4.1%; n=49), of unc-40(e1430) mutants. However, forced expression of unc-40 in body-wall muscles using the myo-3 promoter (Fire et al., 1998) failed to rescue the small body size phenotype (Table 2). As a positive control, expression of unc-40 cDNA under the control of its own promoter was able to rescue the small body size phenotype of unc-40(e1430) mutants (Table 2). Similarly, expression of unc-40 under its own promoter or under the pan-neuronal promoter unc-119 (Maduro and Pilgrim, 1995), but not under hypodermal- or muscle-specific promoters, rescued the axonal migration defects of unc-40(e1430) mutants (Table 2), consistent with the fact that UNC-40 functions as a netrin receptor in neuronal cells to regulate their axonal path finding (Chan et al., 1996). Taken together, our findings are consistent with UNC-40 functioning in the signal-receiving cells to modulate Sma/Mab signaling. Interestingly, forced expression of unc-40 in all neuronal cells using the unc-119 promoter partially rescued the small body size phenotype of unc-40(e1430) mutants (Table 2). This partial rescue could reflect a role of UNC-40 in the signal-producing cells, as the DBL-1 ligand is produced in the ventral nerve cord cells (Morita et al., 1999; Suzuki et al., 1999). Alternatively, it could be an indirect result of the less uncoordinated phenotype of the transgenic animals.

The extracellular domain of UNC-40 is sufficient to modulate Sma/Mab signaling

unc-40 has been studied extensively in terms of its roles in axonal and cell migration (Culotti and Merz, 1998; Bllesloch et al., 1999; Quinn and Wadsworth, 2008; Alexander et al., 2009). Thus, multiple unc-40 alleles exist. To understand which domain of UNC-40 is required for its role in Sma/Mab signaling, we examined multiple unc-40 alleles for body size and SOSMPL phenotypes. Four nonsense mutations, e1430 (R157STOP), ev457 (W460STOP), e271 [R827STOP (Hedgecock et al., 1990; Chan et al., 1996)] and jf59 (Q628STOP), which truncate the extracellular domain of UNC-40, all exhibited highly penetrant small body size and SOSMPL phenotypes (Table 3A). However, ev495 (Q1075STOP; Joe Culotti, personal communication) and tr115 [W1107STOP (Alexander et al., 2009)], which truncate the UNC-40 protein right before and right after the transmembrane (TM) domain, respectively (Table 3A), failed to suppress the sma-9 M lineage phenotype, and the body sizes of ev495 and tr115 mutants were significantly longer than that of e1430 mutants and not statistically different from that of wild-type worms (Table 3A). This is in stark contrast to the axon guidance and cell migration defects shared by all these mutant alleles (Table 3A).

The above findings raised the possibility that the extracellular domain (EXD) of UNC-40 is sufficient to mediate Sma/Mab signaling. To test this hypothesis and to rule out the possibility that potential full-length UNC-40 proteins are present in ev495 and tr115 mutants due to alternative splicing, thus bypassing the nonsense mutations, we generated a transgene containing UNC-40 EXD only rescued the small body size phenotype of ev495 and tr115 mutants due to alternative splicing; instead, UNC-40 EXD is sufficient...
to function in Sma/Mab signaling. These results also suggest that the function of UNC-40 in mediating Sma/Mab signaling is independent from its function in axon guidance and cell migration.

The sixth fibronectin type III motif (FN6) of UNC-40 is essential for its role in Sma/Mab signaling

Our analyses of the unc-40 mutant alleles also suggested that the fifth and sixth fibronectin type III (FNIII) motifs are important for UNC-40 function in Sma/Mab signaling (compare the SOSMLP phenotypes of e271 and ev495 in Table 3A). To test this hypothesis and to rule out the possibility that the phenotypes of these two alleles were due to the absence of mutant UNC-40 proteins as a result of nonsense-mediated decay of the mutant mRNAs, we generated unc-40 transgenes with the fifth or the sixth or both of these FNIII motifs deleted (ΔFN5, ΔFN6 or ΔFN5,6, respectively). Whereas ΔFN5 rescued both the small body size and the SOSMLP phenotypes of the null unc-40(e1430) mutants, ΔFN6 and ΔFN5,6 failed to rescue these two phenotypes (Table 3B). All three deletion constructs completely rescued the axon guidance and cell migration phenotypes of unc-40(e1430) mutants. These results demonstrate that FN6 is absolutely required for the function of UNC-40 in Sma/Mab signaling. Moreover, both FN5 and FN6 are dispensable for the role of UNC-40 in axon guidance and cell migration.

The FN6 motif is required for UNC-40 and DRAG-1 interaction and is essential for UNC-40 function in Sma/Mab signaling

Neogenin, but not DCC, has been shown to directly bind to RGMc through the FN6 motif (Yang et al., 2008). Both neogenin and RGMc have been implicated in BMP signaling (Corradini et al., 2009; Severyn et al., 2009). We have previously shown that the C. elegans RGM protein DRAG-1 is a positive modulator of Sma/Mab signaling (Tian et al., 2010). The finding that the FN6 motif is crucial for UNC-40 function in Sma/Mab signaling led us to hypothesize that UNC-40 might function together with the C. elegans RGM protein DRAG-1 through the FN6 motif. To test this, we transiently expressed the FN5,6 fragment of UNC-40 and the mature portion of DRAG-1 lacking the N- and C-terminal signal sequences in HEK293T cells and performed co-immunoprecipitation (co-IP) assays. We found that FLAG-tagged DRAG-1 could co-immunoprecipitate with Myc-tagged FN5,6 fragment of UNC-40 (Fig. 4C).

To identify the specific sequences in FN6 that are required for the UNC-40–DRAG-1 interaction, we took advantage of the crystal structure of the FN5,6 motifs of human neogenin (Yang et al., 2011). The amino acids involved in neogenin-RGM interaction are predicted to be exposed to the surface of FN6 and to be divergent between human neogenin and DCC (Yang et al., 2011). We also expected them to be conserved among the UNC-40 proteins in different Caenorhabditis species. Based on these criteria, we picked three clusters of amino acids located in the C-C’ strand or E-F loop of the FN6 loop based on the crystal structure of the human neogenin FN6 domain (Yang et al., 2011) (Fig. 4A,B). We tested the importance of each of the three regions by mutating the residues in each region to their corresponding sequences in the human DCC protein. We then examined the consequences of each mutation on the interaction between UNC-40 and DRAG-1 using the co-IP assay and on the in vivo function of UNC-40 using the transgene rescue assay described above. Mutations in the E-F loop, but not those in

<table>
<thead>
<tr>
<th>unc-40 alleles</th>
<th>Transgenes</th>
<th>Unc</th>
<th>Egl (%)</th>
<th>AVM migration defect (%)</th>
<th>Relative body length</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT</td>
<td>None</td>
<td>1 (n&gt;100)</td>
<td>0 (n&gt;100)</td>
<td>0 (n&gt;100)</td>
<td>1.16±0.06*** (n=27)</td>
</tr>
<tr>
<td>unc-40(e1430)</td>
<td>unc-40p::unc-40 cDNA</td>
<td>1.6 (n=50)</td>
<td>16 (n=50)</td>
<td>14.8 (n=108)</td>
<td>1.11±0.04*** (n=73)</td>
</tr>
<tr>
<td>unc-40(e1430)</td>
<td>elt-3p::unc-40 cDNA</td>
<td>2.7 (n=37)</td>
<td>21.6 (n=37)</td>
<td>28.0 (n=118)</td>
<td>1.09±0.05*** (n=62)</td>
</tr>
<tr>
<td>unc-40(e1430)</td>
<td>rol-6p::unc-40 cDNA</td>
<td>2.8 (n=90)</td>
<td>26.7 (n=90)</td>
<td>27.9 (n=106)</td>
<td>1.10±0.04*** (n=60)</td>
</tr>
<tr>
<td>unc-40(e1430)</td>
<td>unc-119p::unc-40 cDNA</td>
<td>1.9 (n=58)</td>
<td>15.9 (n=63)</td>
<td>10.2 (n=117)</td>
<td>1.03±0.04*** (n=70)</td>
</tr>
<tr>
<td>unc-40(e1430)</td>
<td>myo-3p::unc-40 cDNA</td>
<td>2.5 (n=103)</td>
<td>25.4 (n=114)</td>
<td>22.9 (n=109)</td>
<td>1.00±0.05 (n=80)</td>
</tr>
</tbody>
</table>

For axon guidance defects, see supplementary material Fig. S1. Body length was normalized over that of unc-40(e1430) mutants. For all the measurements on transgenic worms in Tables 2-5, data from two transgenic lines were pooled and averaged. ***P<0.0001.

Unc, uncoordinated movement; Egl, egg-laying defective.

Fig. 3. UNC-40 is expressed and functions in the Sma/Mab signal-receiving cells. (A-C) UNC-40::GFP (green) is localized to the cellular membrane of the hypodermal seam cells (arrowheads in A), as indicated by anti-AJM-1 antibody staining (red, B). (D-O) UNC-40::GFP (green, D,G,J,M) is localized to the surface of M lineage cells marked by anti-MLS-2 and anti-FOZ1-1 antibody staining (E,H,K,N) from the 1-M to the 8-M stage. Only one focal plane is shown for the 4-M (J-L) and 8-M (M-O) stage worms.
the C-C' loop and C' strand, abolished both the interaction between UNC-40 and DRAG-1 (Fig. 4C) and the function of UNC-40 in vivo (Table 4). All three mutant unc-40 transgenes could still function in mediating axon guidance (Table 4), again confirming that axon guidance and Sma/Mab signaling are two independent functions mediated by different regions of the UNC-40 protein. These results also indicated that the interaction between UNC-40 and DRAG-1 is crucial for UNC-40 function in Sma/Mab signaling in vivo.

The function of DRAG-1 in modulating Sma/Mab signaling requires DRAG-1–UNC-40 interaction

We next asked whether disrupting the interaction between DRAG-1 and UNC-40 also compromises the function of DRAG-1 in modulating Sma/Mab signaling. Mutations in RGMc (HFE2) cause juvenile hemochromatosis (JH) (Papanikolaou et al., 2004). Previous studies on the JH-causing mutations in RGMc showed that the G320V mutation disrupted the interaction between RGMc and neogenin (Kuns-Hashimoto et al., 2008). Glycine G320 is absolutely conserved and corresponds to G272 in DRAG-1 (supplementary material Fig. S2). We made a corresponding G272V mutation in DRAG-1 and tested its effect on DRAG-1–UNC-40 interaction via the co-IP assay and on DRAG-1 function in vivo using the transgenic rescue assay. DRAG-1G272V exhibited a greatly reduced ability to interact with the FN5,6 fragment of UNC-40 using the transgenic rescue assay. DRAG-1G272V showed that the interaction between UNC-40 and DRAG-1 is crucial for UNC-40 function in Sma/Mab signaling. These results also indicated that for UNC-40, DRAG-1–UNC-40 interaction is crucial for DRAG-1 function in Sma/Mab signaling.

Taken together, our findings suggested that DRAG-1 and UNC-40 are likely to function together to promote Sma/Mab signaling. Consistent with this, genetic epistasis analysis between unc-40 and drag-1 showed that, regarding body size regulation, DRAG-1 and UNC-40 have largely overlapping functions. drag-1(jj4) unc-40(e1430) double mutants are only slightly smaller than either drag-1(jj4) or unc-40(e1430) single mutants (Fig. 2B), which does not appear to be a result of either additive or synergistic effects of the two mutations.

DRAG-1 interacts with both the ligand and receptors of the Sma/Mab pathway

RGM proteins are known to bind the ligand as well as both the type I and type II receptors of the BMP pathway (Babitt et al.,...
Thus, we tested whether DRAG-1 can bind to the ligand and receptors of the Sma/Mab pathway. For co-IP assays we expressed all the factors in HEK293T cells. As a control, the ligand DBL-1 interacts with the type I receptor SMA-6 but not the type II receptor DAF-4 (Fig. 5E), consistent with previous findings that BMP2 and BMP4, the closest homologs of DBL-1, have a higher affinity to type I receptors than to type II receptors (Allendorph et al., 2006). Like its vertebrate homologs, DRAG-1 also interacts with the ligand DBL-1, the type I receptor SMA-6, and the type II receptor DAF-4 (Fig. 5D,E).

The interaction between DRAG-1 and DBL-1 also appears to be important for DRAG-1 function in vivo. A G68V mutation in DRAG-1, which corresponds to G99V in human RGMc, which disrupts RGMc-BMP interaction (Kuns-Hashimoto et al., 2008), significantly affected the function of DRAG-1, as the drag-1G68V transgene only partially rescued the small body size and SOSMLP phenotypes of drag-1(jj4) mutants (Fig. 5A, Table 5).

**Table 4. Rescue of axon guidance defects (Unc, Egl and AVM migration) and Sma/Mab signaling defects (body size and SOSMLP) of unc-40(e1430) mutants by various unc-40 transgenes**

<table>
<thead>
<tr>
<th>unc-40 alleles</th>
<th>Transgenes</th>
<th>Unc</th>
<th>Egl (%)</th>
<th>AVM migration defect (%)</th>
<th>Relative body length</th>
<th>SOSMLP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT</td>
<td>None</td>
<td>1</td>
<td>(n&gt;100)</td>
<td>0 (n&gt;100)</td>
<td>1.16±0.06*** (n=27)</td>
<td>N.A.</td>
</tr>
<tr>
<td>unc-40(e1430)</td>
<td>None</td>
<td>3.0</td>
<td>(n=54)</td>
<td>33.3 (n=54)</td>
<td>25.4 (n=51)</td>
<td>1.00±0.04 (n=50) 88.7 (n=150)</td>
</tr>
<tr>
<td>unc-40(e1430)</td>
<td>unc-40 WT</td>
<td>2.3</td>
<td>(n=101)</td>
<td>25.7 (n=101)</td>
<td>14.5 (n=117)</td>
<td>1.12±0.05*** (n=51) 1.8 (n=57)</td>
</tr>
<tr>
<td>unc-40(e1430)</td>
<td>unc-40 C-C</td>
<td>1.2</td>
<td>(n=111)</td>
<td>22.1 (n=104)</td>
<td>18.8 (n=106)</td>
<td>1.13±0.05*** (n=51) 0 (n=108)</td>
</tr>
<tr>
<td>unc-40(e1430)</td>
<td>unc-40 C</td>
<td>1.3</td>
<td>(n=114)</td>
<td>18.3 (n=104)</td>
<td>15.7 (n=108)</td>
<td>1.11±0.06*** (n=54) 3.9 (n=158)</td>
</tr>
<tr>
<td>unc-40(e1430)</td>
<td>unc-40 E-F</td>
<td>1.3</td>
<td>(n=103)</td>
<td>25.2 (n=103)</td>
<td>16.7 (n=114)</td>
<td>1.01±0.05 (n=43) 81.8 (n=143)</td>
</tr>
</tbody>
</table>

***P<0.0001.
size and SOSMLP phenotypes of drag-1(jj4) mutants (Table 5). Similarly, a hybrid transgene with the signal sequence of mouse neogenin (Neo1) replaced by that of UNC-40 could partially rescue the small body size and SOSMLP phenotypes of drag-1(jj4) mutants (Table 3B). These results suggest that DRAG-1 and UNC-40 and their corresponding vertebrate counterparts share evolutionarily conserved functions in modulating BMP signaling.

**Mouse neogenin does not require its intracellular domain to promote BMP signaling**

We have described that the EXD of UNC-40 is sufficient to mediate Sma/Mab signaling in *C. elegans*. Because of the functional conservation between UNC-40 and mouse neogenin, we next tested whether mouse neogenin requires its ICD to promote BMP signaling using two independent assays. First, we expressed full-length neogenin (Neo) or neogenin with the ICD deleted (NeoΔICD) in HEK293 cells and determined their effect on BMP2-stimulated phosphorylation of Smad1/5/8. Both Neo and NeoΔICD enhanced BMP2-stimulated phosphorylation of Smad1/5/8 to a similar extent (Fig. 6A,B). Second, we transfected Neo and NeoΔICD into primary fibroblast cells derived from neogenin hypomorphic mutant mice (Zhou et al., 2010) and determined their ability to rescue the defective expression of a BMP signaling reporter (9XsBE-Luc) upon BMP2 stimulation. Both Neo and NeoΔICD restored the BMP2-stimulated expression of the BMP signaling reporter to a similar extent (Fig. 6C). These results demonstrate that, like *C. elegans* UNC-40, the ICD of mouse neogenin is not required for proper BMP signaling.

**DISCUSSION**

**UNC-40/neogenin positively modulates BMP signaling**

As a close homolog of DCC, neogenin was initially recognized as an axon guidance receptor that is required for axon and cell migration (Cole et al., 2007; Wilson and Key, 2007; Yamashita et al., 2007). Recent reports suggest that neogenin is also involved in modulating BMP signaling, but how it does so has been controversial (Tian and Liu, 2013). On the one hand, neogenin positively potentiates BMP signaling to regulate the expression of hepcidin for body iron metabolism and endochondral ossification in mice (Lee et al., 2010; Zhou et al., 2010) or human liver cells (Zhang et al., 2009). On the other hand, neogenin negatively modulates BMP2-induced osteoblastic differentiation of C2C12 cells (Hagihara et al., 2011). Neogenin also increases the secretion of soluble RGMc, which may cause downregulation of BMP signaling (Zhang et al., 2005; Zhang et al., 2007).

Our findings clearly demonstrate that the sole DCC/neogenin homolog UNC-40 is a positive modulator of the BMP-like Sma/Mab pathway in *C. elegans*: (1) unc-40(0) mutants share similar body size and SOSMLP phenotypes with those of Sma/Mab pathway loss-of-function mutants; (2) unc-40(0) mutants exhibit reduced activity of the Sma/Mab reporter, RAD-SMAD; and (3) unc-40 acts in the Sma/Mab pathway to regulate body size, as indicated by the genetic epistasis analysis. We further showed that UNC-40 functions at the ligand-receptor level in the signal-receiving cells to modulate Sma/Mab signaling. Because mouse neogenin can partially rescue the Sma/Mab pathway phenotypes of unc-40(0) mutants, we suggest that, like its function in axon guidance and cell migration, the function of UNC-40 in modulating BMP signaling is also evolutionarily conserved.

**UNC-40 independently mediates BMP signaling and netrin signaling**

DCC is well established as a receptor for netrin in axon guidance and migration (Kennedy et al., 1994; Colavita and Culotti, 1998; Hong et al., 1999; Qin et al., 2007). Unlike DCC, which does not bind RGM proteins, neogenin can bind to both netrin and RGM proteins. Interestingly, we found that the ICD of mouse neogenin is not required for proper BMP signaling. This suggests that the ICD of mouse neogenin is not required for proper BMP signaling.

**Table 5. Body size and SOSMLP phenotypes of drag-1(jj4) mutants expressing various transgenes**

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Relative body length</th>
<th>SOSMLP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT</td>
<td>1.18±0.05*** (n=48)</td>
<td>N.A.</td>
</tr>
<tr>
<td>drag-1(jj4)</td>
<td>1.10±0.05 (n=50)</td>
<td>98.5 (n=201)</td>
</tr>
<tr>
<td>drag-1(jj4) + drag-1 cDNA</td>
<td>1.10±0.06*** (n=25)</td>
<td>82.1 (n=106)</td>
</tr>
<tr>
<td>drag-1(jj4) + mouse Rgmb cDNA</td>
<td>1.04±0.04*** (n=34)</td>
<td>85.4 (n=82)</td>
</tr>
<tr>
<td>drag-1(jj4) + human Rgmc cDNA</td>
<td>1.03±0.04*** (n=72)</td>
<td>76.6 (n=143)</td>
</tr>
<tr>
<td>drag-1(jj4) + Mos-SCI drag-1::gfp</td>
<td>1.17±0.04*** (n=96)</td>
<td>1.2 (n=498)</td>
</tr>
<tr>
<td>drag-1(jj4) + Mos-SCI drag-1(G68V)::gfp</td>
<td>1.02±0.04* (n=47)</td>
<td>79.3 (n=554)</td>
</tr>
<tr>
<td>drag-1(jj4) + Mos-SCI drag-1(D127E)::gfp</td>
<td>1.04±0.04*** (n=76)</td>
<td>0.8 (n=515)</td>
</tr>
<tr>
<td>drag-1(jj4) + Mos-SCI drag-1(G272V):gfp</td>
<td>1.01±0.04 (n=98)</td>
<td>94.9 (n=414)</td>
</tr>
</tbody>
</table>

Body length was normalized to that of drag-1(jj4) mutants. Data are mean ± s.d. **P<0.0001, *P<0.05, drag-1(jj4) versus worms of different genotypes (Student’s t-test).**
proteins, and it has netrin-dependent roles in axon guidance, cell-cell adhesion and tissue organization (Srinivasan et al., 2003; Kang et al., 2004; Wilson and Key, 2006; Lejmi et al., 2008) and functions in BMP signaling (Zhang et al., 2009; Zhou et al., 2010). We have shown that, in addition to its previously reported roles in netrin-mediated axon guidance and cell migration, the single C. elegans DCC/neogenin homolog UNC-40 is capable of promoting BMP signaling by binding to the RGM protein DRAG-1. Importantly, these two functions of UNC-40 are independent of each other: (1) null mutations in genes that encode UNC-6/netrin and another netrin receptor, UNC-5, do not cause any defects in Sma/Mab signaling; (2) UNC-40 protein lacking the ICD is defective in netrin-mediated axon guidance and cell migration, but exhibits wild-type activity in Sma/Mab signaling; and (3) UNC-40 proteins lacking the sixth FNIII motif (FN6), or carrying mutations in the E-F loop of FN6, are defective in Sma/Mab signaling, but exhibit wild-type activity in netrin-mediated axon guidance and migration. Importantly, the role of UNC-40 in promoting Sma/Mab signaling requires its interaction with the RGM protein DRAG-1, which on its own does not appear to play any significant role in axon guidance and cell migration (our unpublished data). These findings suggest that, rather than acting as a convergent point between the netrin-mediated pathway and the BMP pathway, neogenin independently mediates these two pathways via distinct effectors. Although the ICD is clearly required for UNC-40/neogenin to mediate netrin signaling in axon guidance, it is dispensable for the role of UNC-40/neogenin in mediating BMP signaling. Consistently, the netrin-binding motif and the RGM-binding motif have been mapped to two independent regions of neogenin (Rajagopalan et al., 2004).

Our finding that the EXD of UNC-40 is sufficient to mediate BMP signaling suggests the intriguing possibility that UNC-40 might undergo proteolytic processing in vivo to release its EXD. In fact, both DCC and neogenin have previously been reported to undergo metalloprotease-mediated ectodomain shedding (Galko and Tessier-Lavigne, 2000; Okamura et al., 2011). Whether UNC-40 undergoes ectodomain shedding, and, if so, how this process is regulated spatially and temporally will be areas of future investigation.

A model for UNC-40/neogenin function in regulating BMP signaling

Results from our in vitro and in vivo experiments demonstrated that the EXD of UNC-40 binds to DRAG-1 and that this interaction is crucial for their function in Sma/Mab signaling. Moreover, both

Fig. 6. Mouse neogenin lacking the intracellular domain is sufficient to mediate BMP signaling. (A) Western blot showing BMP2-induced pSmad1/5/8 in HEK293 cells expressing neogenin and neogeninΔICD. (B) Quantitative analysis of data from A. The levels of phosphorylation of Smad1/5/8 were quantified by ImageJ and normalized with the control. Data are mean ± s.d., n=3; *P<0.05 versus control (Student’s t-test). (C) Rescue of defective BMP reporter expression by both neogenin and neogeninΔICD. Wild-type and neogenin mutant fibroblasts were transiently transfected with vector (control), neogenin, or neogeninΔICD plus the BMP signaling reporter plasmid (9XSBE-Luc). Two days after transfection, cells were stimulated with BMP2 (see Materials and methods). Luciferase activity was measured, normalized to the control without BMP2, and presented as mean ± s.d. of triplicates from a representative experiment. *P<0.05 versus the absence of BMP2 stimulation (Student’s t-test).

Fig. 7. A model of UNC-40 function in promoting BMP signaling. By interacting with DRAG-1 through its FN6 motif and through interactions with other, as yet unidentified, factors (???) UNC-40 allows an increased local concentration or stability of the ligand-receptor complex on the surface of the signal-receiving cell, thereby promoting Sma/Mab signaling. UNC-40 protein might be processed via ectodomain shedding. The intracellular domain (ICD) of UNC-40 is depicted in dotted outline, as it is not required for Sma/Mab signaling. UNC-40 might also function in the signal-producing cells, which is not depicted here.
proteins function in cis in the same signal-receiving cells to promote BMP signaling (Tian et al., 2010) (this study). Because DRAG-1 binds to both the ligand and the receptors of the Smad/Mab pathway, we propose that the binding of UNC-40 to DRAG-1 might allow an increased local concentration or stability of the ligand/receptor complex, thereby promoting Smad/Mab signaling (Fig. 7). This is consistent with a model proposed by Zhou and colleagues in which neogenin positively modulates BMP signaling by promoting the formation of BMP-induced super-receptor complexes that include RGMs, neogenin and BMP receptors in membrane microdomains (Zhou et al., 2010).

DRAG-1, however, does not appear to be the only factor that interacts with UNC-40 to mediate its function in Smad/Mab signaling: (1) cell fractionation experiments showed that the EXD of UNC-40 is membrane associated and that this association is independent of DRAG-1 (data not shown); and (2) two additional unc-40 alleles – ev546, which carries a G774R mutation in the FN4 motif (Alexander et al., 2010), and tm5504, which deletes the FN1 and FN2 motifs, exhibit incompletely penetrant SOSMLP phenotypes [12.16% (n = 74) for ev546 and 39.5% (n = 215) for tm5504].

Future work will be directed towards identifying the other factors that interact with UNC-40 and how they function together to allow efficient BMP signaling. In light of the importance of the BMP pathway in regulating multiple developmental and homeostatic processes and the fact that mutations in RGMs cause JH, results from these studies are likely to have significant implications.

Acknowledgements
We thank the Caenorhabditis Genetics Center (CGC) (funded by the National Institutes of Health, Office of Research Infrastructure Programs P40 OD010440), Daniel Colon-Ramos, Joe Culotti, Eric Jorgensen, Keith Nehrke, Shohel Mitani, Peter Roy, Tarek Samad, Kang Shen, Stephen Strittmatter, William Wadsworth and Yinming Zhou for strains and plasmids; Joe Culotti for sharing unpublished results; and Ken Kemphues, Mariana Wolner and members of the J.L. lab for comments and suggestions.

Funding
This work was supported by grants from the National Institutes of Health [NIH GM066953 to J.L.; and NIH NS06646 to W.-C.X.] and from the Department of Veterans Affairs [VA BX00838 to W.-C.X.]. Deposited in PMC for release after 12 months.

Competing interests statement
The authors declare no competing financial interests.

Author contributions
C.T., H.S. and J.L. performed the experiments; S.X. performed the experiments presented in Fig. 6 under the supervision of W.-C.X.; F.H. provided reagents and contributed to discussion of the data; C.T. and J.L. conceived the project, designed the experiments, analyzed the data and wrote the manuscript.

Supplementary material
Supplementary material available online at http://dev.biologists.org/lookup/suppl/doi:10.1242/dev.099838/-/DC1

References


