RNA-binding protein GLD-1/quaking genetically interacts with the mir-35 and the let-7 miRNA pathways in Caenorhabditis elegans

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1. Summary

Messenger RNA translation is regulated by RNA-binding proteins and small non-coding RNAs called microRNAs. Even though we know the majority of RNA-binding proteins and microRNAs that regulate messenger RNA expression, evidence of interactions between the two remain elusive. The role of the RNA-binding protein GLD-1 as a translational repressor is well studied during Caenorhabditis elegans germline development and maintenance. Possible functions of GLD-1 during somatic development and the mechanism of how GLD-1 acts as a translational repressor are not known. Its human homologue, quaking (QKI), is essential for embryonic development. Here, we report that the RNA-binding protein GLD-1 in C. elegans affects multiple microRNA pathways and interacts with proteins required for microRNA function. Using genome-wide RNAi screening, we found that nhl-2 and vig-1, two known modulators of miRNA function, genetically interact with GLD-1. gld-1 mutations enhance multiple phenotypes conferred by mir-35 and let-7 family mutants during somatic development. We used stable isotope labelling with amino acids in cell culture to globally analyse the changes in the proteome conferred by let-7 and gld-1 mutants. We identified the histone mRNA-binding protein CDL-1 to be, in part, responsible for the phenotypes observed in let-7 and gld-1 mutants. The link between GLD-1 and miRNA-mediated gene regulation is further supported by its biochemical interaction with ALG-1, CGH-1 and PAB-1, proteins implicated in miRNA regulation. Overall, we have uncovered genetic and biochemical interactions between GLD-1 and miRNA pathways.

2. Introduction

microRNAs (miRNAs) are approximately 21 nucleotide-long endogenous regulatory RNAs that mediate translational regulation through binding to
the 3’UTR of target mRNAs. Over the past decade, they have been implicated in many biological processes and are now considered to be major modulators of gene expression [1,2]. After biogenesis, miRNAs and Argonaute proteins (AGO; ALG-1/ALG-2 in C. elegans) form the miRNA-induced silencing complex (miRISC) together with GW182 proteins (AIN-1/AIN-2 in C. elegans) [3]. VIG-1 is thought to function in the miRNA pathway and was identified as an interactor of miRNA/Argonaute complexes by co-immunoprecipitation [4]. Mammalian TRIM32 and C. elegans NTL-2 also interact with AGO and promote miRNA activity [5,6].

GLD-1 is a member of a highly conserved RNA-binding protein family, characterized by the signal transduction and activation of RNA (STAR) domain [7]. GLD-1 affects germ line development and maintenance by translational repression of a variety of target genes [8–14]. A key role for GLD-1 in modulating DNA damage-induced germ line apoptosis was uncovered via the hypomorphic gld-1(op236) allele [13]. In gld-1(op236) mutants, GLD-1 is unable to bind the 3’UTR of cep-1/p53, whereas translational repression of GLD-1 targets mediating development is unaffected. gld-1(op236) is unique among gld-1 alleles in showing no overt defect in germ cell development at the permissive temperature. However, at the restrictive temperature, gld-1(op236) animals are sterile, and undifferentiated germ cells accumulate [13]. The mammalian orthologue of GLD-1 is quaking/QKI, which functions in translational regulation during neuronal development [15,16]. GLD-1 and QKI are functionally conserved, and ectopically expressed QKI in worms recognizes GLD-1 target sequences [17]. Although GLD-1 biochemically interacts with AIN-2, the functional consequences of this interaction have not yet been determined [18]. Lastly, miRNA-related functions of gld-1 have not been documented by mutational analysis, and a gld-1 phenotype affecting somatic development of animals has not been reported.

Deleting the vast majority of known C. elegans miRNAs individually does not result in obvious overt phenotypes [19]. Phenotypes tend to arise when several members of a miRNA family are deleted [20]. Alternatively, mutating miRNA pathway genes also generate sensitized system that helps us to unravel miRNA function [21]. Such synthetic phenotypes point towards the existence of extensive redundancy in miRNA-mediated gene regulation. Caenorhabditis elegans genetics allows for using ‘sensitized’ genetic backgrounds to study subtle phenotypes associated with redundant mechanisms of miRNA-mediated gene regulation.

Initially aiming to identify genes required for GLD-1-mediated translational regulation, we performed a genome-wide RNAi screen for enhancers of the gld-1(op236) hypomorphic allele. This screen identified vig-1 and nhl-2, both of which are modulators of miRNA function, thus suggesting that GLD-1 might affect general miRNA-mediated gene regulation. We indeed found that gld-1 enhances multiple let-7 and mir-35 family miRNA phenotypes affecting somatic development. Using stable isotope labelling with amino acids in cell culture (SILAC)-based proteomics, we show that the upregulation of the histone miRNA-binding protein CDL-1 is partially responsible for the genetic interactions between GLD-1 and let-7 miRNA. A role for GLD-1 in miRNA-mediated gene regulation is further supported by the interaction of GLD-1 with ALG-1, CGH-1 and PAB-1, proteins previously implicated in miRNA-mediated gene regulation.

3. Material and methods

3.1. Strains and animal handling

Strains used in this paper were TG34 gld-1(op236)I, TG2209 vig-1(ok2536)I, TG2129 gld-1(op236)I, vig-1(ok2536)I, TG1725 nhl-2(ok181)III, TG2130 gld-1(op236)I, nhl-2(ok181)III, MT14119 nD50II, TG2133 gld-1(op236)I, nD50II, GR1432 let-7(mg279)X, TG1684 gld-1(op236)I, let-7(mg279)X, VT1142 nD51V; mir-84 (n4037)I, cts39, TG2134 gld-1(op236)I, nD51V; mir-84 (n4037)I, tsa39, SU93 jcs11V, TG2017 gld-1(op236)I, jcs11V; let-7(mg279)X, TG2019 gld-1(op236)I, jcs11V; let-7(mg279)X, MT1214 let-60(n1046)IV, TG2135 gld-1(op236)I; let-60(n1046)IV, SD551 let-60(ga89)IV, TG2136 gld-1(op236)I; let-60(ga89)IV, TG1828 mals105V, TG1825 gld-1(op236)I; mals105V, TG1826 gld-1(op236)I; let-7(mg279)X, TG1827 gld-1(op236)I; mals105V; let-7(mg279)X, TG2137 gld-1(op236)I; HT2 I; mals105V; let-7(mg279)X, TG2138 gld-1(op236)I; let-7(g485)I; mals105V; let-7(mg279)X, TG2131 gld-1(op236)I; let-7(g485)I; vig-1(ok2536)I, mals105V, SX493 Pcol-10::GFP::lin-41–3’UTR(mjs32) II, TG2039 Pcol-10::Gld-1::mCherry:glad-1–3’UTR(qEx2039), TG2139 Pcol-10::GFP::lin-41–3’UTR(mjs32) II; Pcol-10::Gld-1::mCherry:glad-1–3’UTR(qEx2039), TG2041 Pcol-10::Gld-1::mCherry::H2B::glad-1–3’UTR(qEx2041), SX1257 Pcol-10::GFP::lin-41–3’UTR(mjs32) II; Peat-10::mCherry::unc-54–3’UTR(mjs177) IV, TG2212 Pcol-10::GFP::lin-41–3’UTR(mjs32) II; Peat-10::mCherry::unc-54–3’UTR(mjs177) IV; let-7(mg279), TG2213 gld-1(op236)I; Peat-10::GFP::lin-41–3’UTR(mjs32) II; Pcol-10::GFP::lin-41–3’UTR(mjs177) IV; let-7(mg279), TG1769 gld-1(op236)I; Peat-10::GFP::lin-41–3’UTR(mjs32) II; Pcol-10::mCherry::unc-54–3’UTR(mjs177) IV, OZ152 gld-1::GFP::FLAG; gld-1(q485)I (ozi32), SX2695 gld-1(op236)I; col-10::GFP::lin-41 deletion (mjs35) II; unc-119(ed3) III; let-7(mg279) X, SX2696 gld-1(op236)I; col-10::GFP::lin-41 deletion (mjs35) II; unc-119(ed3) III, SX2697 col-10::GFP::lin-41 deletion (mjs35) II; unc-119(ed3) III; let-7(mg279) X, SX2279 col-10::GFP::lin-41 deletion (mjs35) II; unc-119(ed3) III.

Caenorhabditis elegans larvae were grown on Escherichia coli strain OP50 at 20°C unless otherwise stated. let-60(ga89) mutants were grown at 20°C and their progeny was shifted to 25°C at the L1 larval stage and scored at adult stage for the presence of multi-vulva phenotype. Microscopic analysis of the animals was carried out by anaesthetizing with levamisole and observed using a Zeiss axioscope.

3.2. RNAi in Caenorhabditis elegans

We used the whole-genome RNAi library generated by Abringer Laboratory [22,23], and a modified version of the RNAi feeding protocol described in [24]. RNAi-expressing bacteria were grown from frozen stocks overnight at 37°C in LB medium containing 50 μg ml−1 ampicillin and 10 μg ml−1 tetracycline in 96-well plates. A fresh culture seeded from the overnight culture was incubated at 37°C in 96-deep-well plates until OD600nm was 0.6–1 and then induced with 1 mM IPTG for 2 h at 20°C. L1 larvae were dispersed into 96-well plates (10 worms well−1) in 100 μl M9 medium supplemented with 50 μg ml−1 ampicillin, 10 μg ml−1 tetracycline, 10 μg ml−1 cholesterol, 0.1 μg ml−1 fungizone and 1 mM IPTG. Induced bacteria (50 μl) were also dispensed into each well, and worms were grown at 20°C with constant shaking at
180 r.p.m. The presence of progeny was scored after 4–5 days. To validate candidates from the RNAi screen, 500–1000 L1 larva were treated with RNAi in 50 ml falcon tubes. Volumes of M9 medium and bacterial culture were scaled up accordingly. RNAi of GLD-1 protein interactors and gfp-1 was performed in a similar manner in 50 ml falcon tubes, and worms were transferred to plates seeded with the RNAi bacteria at L2–L3 stage. Number of assayed animals is presented on related figures.

3.3. Generation of transgenic lines

The pgld-1::mCherryHis::gld-1–3’UTR (GA-AA006, gtEx2041) construct was generated by cloning the gld-1 promoter (amplified using primers 5’-atatatagggccgtCTGAT TCAITTTTATAAACACTCG-3’ and 3’-atatatatgaggccggcTCTT CGATGGTTAACTGTGAAG-5’ from genomic DNA) using Ascl and NotI enzymes. mCherryHis was amplified using primers 5’-atatatagggccgtATGGTCTCCTTGAATCGAG-3’ and 3’-atatatatgaggccggcTTCGATTAACAGTACTCATTG-5’, and digested with NotI and FseI. The gld-1 3’UTR was amplified using primers 5’-atatatatattataappAAAGTTAACCTTA TAACTCTCACTC-3’ and 3’-atatatagggccggcTTGAATAAA AACTATTATTATTATTACTC-5’ from genomic DNA and digested with PacI and Apal. All fragments were cloned into a vector containing the unc-T19(+/-) selectable marker [25]. The resulting construct was injected into worm gonads at 100 ng µl⁻¹ concentration. pocl-10::GFP::glp-1–3’UTR (GA-AA010, gtEx2039) construct was generated by PCR amplification of the col-10 promoter using primers 5’-atatagggccggcgTGTCCGATTAATCCCTTACA-3’ and 3’-atatatgaggccggcGACTGAGCGGTAAGACAA ACTATTATTATTATTATTACTC-5’ from genomic DNA and digested with NotI and FseI. The gld-1 coding region was amplified from genomic DNA using primers 5’-atatagggccggcgAGTCCGTCGTCACACTC-3’ and 3’-atatatatagggccggcGAAAAGAGGTTGTGACTG-5’ and digested with NotI and FseI. mCherry was amplified using primers 5’-atatatagggccgctGATnTCTCCTTGAATCGAG-3’ and 3’-atatatatgaggccggcTTACGATTAACAGTACTCATTG-5’, and digested with FseI and Apal. The gld-1 3’UTR was amplified as described above. DNA fragments were cloned into same backbone as above, and transgenic lines were generated by particle bombardment (PDS-100/He biolistic particle delivery system, Bio-Rad; [26]). mjs32, mjs117, mjs635 constructs were generated using the col-10 promoter, GFP and mCherry coding sequences and the lin-41 and unc-54 3’UTRs as previously described [27,28] using transposon-mediated homologous recombination [29]. Lin-41 deletion 3’UTR was constructed using the primers 5’-CTGGGGAATTTCAaaaattggtt gcattttttggaaaactac-3’ and 5’-GAATTITGGGAATTTCCcaatattt gatttaagctcctca-3’.

3.4. Immunoprecipitation

Anti-GLD-1 antibodies generated in our laboratory were used for GLD-1 immunoprecipitation [30]. Frozen N₂ wild-type worm pellets (approx. 300 µl) were thawed in 2× volume lysis buffer (10 mM Tris–HCl, pH 7.5, 150 mM NaCl, 0.5 mM EDTA, 0.5% NP40, Roche mini complete protease inhibitor cocktail, 1 mM PMSF), lysed by bead beating (3 × 20 s, with 20 s intervals) with 300 µl 0.7 mm zirconia beads at 4°C. Lysates were incubated on ice for 30 min and then clarified at 13 000 r.p.m. for 10 min, 4°C. Lysate (2 µg) pre-cleared with protein G sepharose beads was incubated with 1 µg of rabbit anti-GLD-1 antibody for 1 h at 4°C or no-Ab beads, then added to 50 µl protein G sepharose beads and incubated for a further 1 h at 4°C. Beads were washed twice with wash buffer (10 mM Tris–HCl pH 7.5, 300 mM NaCl, 0.5 mM EDTA, 1× protease inhibitor cocktail, 1 mM PMSF), then protein complexes were eluted with 20 µl SDS sample buffer, separated on SDS gels, silver-stained and analysed by mass spectrometry. Immunoprecipitation of GFP–GLD-1 complexes from gld-1 (gq855)::zol52 [gld- 1::gfp::FLAG] [13] was carried out as described previously [31].

3.5. Northern blotting

Total RNA was extracted using Qiazol (Qiagen) with 300 µl of 0.7 mm zirconia beads at 4°C from synchronized adult-stage worms and separated on 15% polyacrylamide gels (SequagelFlowGel). Gels were blotted onto Hybond-N (Amersham) membrane using a semi-dry electro bloter, and chemical cross-linking was carried out using l-ethyl-3-3-dimethylamino-propyl carbodiimide (EDC) as previously described [32]. Blots were probed with labelled let-7 RNA and U6 snRNA DNA oligonucleotides as previously described [33].

3.6. SILAC in nematodes

SILAC growth conditions, subcellular fractionations, peptide preparations and mass spectrometry were carried out as described in [34–36]. The number of proteins detectable by mass spectrometry was increased by subfractional collection [34]. For determining B to A and C to A ratios, we considered proteins that were only detected in one experiment if a minimum of two peptides were detected (the detection of two or more independent peptides all passing though MAXQUANT adding to the statistical significance [37]). We also considered proteins detected in two independent experiments but excluded those whose the standard error of the mean based on multiple detected peptides from the same protein was bigger than the mean. In the B to A comparison, 2708 proteins passed those criteria, whereas 2927 passed in the C to A comparison. We focused on the 2179 proteins that were reliably detected in both datasets (see electronic supplementary material, table S1).

4. Results

4.1. A genetic screen identifies vig-1 and nhl-2 as enhancers of gld-1(op236)

We performed a genetic screen to search for genes whose inactivation enhances the gld-1(op236) defect. gld-1(op236) animals have wild-type germlines at 20°C but are sterile at 25°C [13]. In a whole-genome RNAi feeding screen, we looked for genes whose depletion by RNAi causes sterility at 20°C specifically in gld-1(op236) mutants but not in wild-type animals (figure 1a). Out of over a hundred initial candidates (data not shown), 20 reproducibly showed reduced progeny in the gld-1(op236) background (figure 1b). Of these, deletions were available for seven candidates, and double mutants of five of these with gld-1 confirmed the reduced progeny or sterility phenotype observed in the RNAi screen. A detailed analysis of synthetic phenotypes with hecd-1, ced-1 and lar-1 will be described elsewhere.
Interestingly, *vig-1* and *nhl-2* were previously identified as modulators of the miRNA pathway [4,5].

We observed that a significant portion of *gld-1(op236)*; *nhl-2(op8818)* animals are sterile and have stacked oocytes in their germlines and no fertilized embryos in the uterus (electronic supplementary material, figure S1a,b). Analysis of *gld-1* (*op236*); *vig-1* (*ok2536*) animals revealed that the entire germline fills with undifferentiated cells and animals become sterile within 12 h of reaching adult stage (electronic supplementary material, figure S1c,d). In addition, embryos laid from these animals show a highly penetrant embryonic lethality phenotype (electronic supplementary material, figure S1e). The sterility phenotypes of the *gld-1* (*op236*); *nhl-2(op8818)* and *gld-1* (*op236*); *vig-1* (*ok2536*) double mutants confirm the results of our RNAi screen.

Unexpectedly, 29% of the surviving *gld-1* (*op236*); *vig-1* (*ok2536*) larvae have arrested development and abnormal somatic morphology (figure 1c,d). ‘Extruding bumps’ are readily observed at various positions along the body axis of these animals. Using the *col-19::GFP* hypodermal cell marker, we found that hypodermal cells accumulate in these protrusions rather than being regularly spaced along the body axis (figure 1c). In addition, double-mutant animals appear shorter and sick. Sterility and embryonic lethality phenotypes have already been described for *dcr-1* (dicer endonuclease) mutants as well as for *alg-1*/*alg-2* Argonaute double mutants [38–40]. Given this similarity, and as both *VIG-1* and *NHL-2* modulate miRNA function, we decided to investigate possible genetic interactions between *gld-1* and miRNAs.

### 4.2. *gld-1* genetically interacts with *mir-35* family miRNAs

To investigate an interaction between *gld-1* and miRNAs, we started by making double mutants of *gld-1* (*op236*) and *mir-35* family miRNAs. The *mir-35* family of miRNAs comprises eight members (*mir-35–42*), which are highly enriched in oocytes [20] and are required for embryonic development. While *mir-35* family mutants do not individually exhibit an observable phenotype, combined mutation of either all or most *mir-35* family members causes severe embryonic and larval lethal phenotypes [20], similar to those we observed in the *gld-1* (*op236*); *vig-1* (*ok2536*) double mutant. The expression pattern and phenotypes of *mir-35* family miRNAs make them suitable to investigate possible genetic interactions with *gld-1*.

A deletion mutant, *ndf50*, which removes all *mir-35* family miRNAs except for *mir-42*, causes a temperature-sensitive embryonic and early larval lethality [20]. At 20°C, we observed that 33% of *mir-35–41* (*ndf50*) animals die either during embryogenesis or at the L1 larval stage. In *gld-1* (*op236*); *mir-35–41* (*ndf50*) double-mutants embryonic and larval lethality increases to 67%, indicating a strong genetic interaction between *gld-1* and the *mir-35* miRNA family (figure 2a, left). Given that both *mir-35–41* (*ndf50*) and *gld-1* (*op236*); *mir-35–41* (*ndf50*) mutants lay similar numbers of eggs (figure 2a, right), the synthetic interaction between *gld-1* and *mir-35* family miRNAs must specifically affect early embryonic development.

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**Figure 1.** Whole genome RNAi screen identifies enhancers of *gld-1* (*op236*). (a) Schematic of the RNAi screen. (b) List of candidate genes with various levels of reproducibility indicated. Owing to variations in the effectiveness of RNAi, further validation was carried out by the analysis of mutants (genes marked with + or −) and five out of seven genes validated the RNAi results when tested with mutants (+). (c,d) Somatic defects in *gld-1* (*op236*); *vig-1* (*ok2536*) larvae develop an abnormal morphology, as indicated by arrowheads (*p < 0.01, Fisher’s exact test). Left panel DIC image, right panel fluorescent image of the same animal that expresses *col-19::GFP*. As a control, wild-type animals are shown at the lower panel.
Figure 2. gld-1 genetically interacts with mir-35 and let-7 family miRNAs. (a) Adult animals 24 h past L4 stage were allowed to lay eggs and quantitation of embryonic and larval lethality is depicted for mir-35; 41(nD50) and gld-1(op236); mir-35 – 41(nD50) mutants at 20°C (left graph). gld-1(op236) animals are 100% viable. Number of eggs laid per worm is shown in the right graph. Each experiment was carried out in quadruplicate (n > 250), and the percentage of dead eggs and L1 worms was calculated (error bars = s.e.m.). (b) Lethality owing to adult-stage lethargus. Number of assayed worms is mentioned in parenthesis. m, maternal genotype; z, zygotic genotype. Synchronized L1 stage animals were grown to adult stage and assayed for lethality owing to internal hatching of embryos. Owing to the sterility of gld-1(null) animals, gld-1(null); let-7(mg279) phenotype is determined by slow movement and lack of pharyngeal activity during L4 to young adult transition. (c) Representative picture of a gld-1(op236); let-7(mg279) worm. The accumulation of late stage embryos is evident. Arrowhead indicates cuticle that failed to shed.

4.3. gld-1 genetically interacts with let-7 family miRNAs

Next, we decided to investigate whether gld-1 can genetically interact with other miRNA families. The let-7 family (let-7, mir-48, mir-84, mir-241 and mir-79b) miRNAs are much more studied compared with mir-35 family miRNAs during C. elegans development. One of the phenotypes in let-7 mutants relates to molting [41]. Caenorhabditis elegans has four larval stages, and each larval stage ends with a molt. Moulting starts with a sleep-like stage called lethargus during which worms slow down feeding and movement. During lethargus, a new cuticle is synthesized, and moulting ends with the removal of the old cuticle [42]. A supernumerary fifth molt has been described in let-7(mg279); mir-84(tm1304) double mutants [41], during which adult animals cease to move and stop pharyngeal activity. Subsequently, affected animals fail to lay eggs and die owing to the internal hatching of embryos.

We did not observe such a phenotype in gld-1(op236) and in the hypomorphic let-7(mg279) single mutant, but to our surprise, this phenotype occurred in 84% of gld-1(op236); let-7(mg279) double mutants (figure 2b and electronic supplementary material, movie S1). The mg279 allele has a promoter mutation that reduces let-7 expression [43]. As previously observed for let-7(mg279); mir-84(tm1304) double mutants [41], gld-1(op236); let-7(mg279) animals with only partially shed cuticles can be observed (figure 2c). gld-1(q485) null; gld-1(op236); let-7(mg279) and gld-1(q485) null; let-7(mg279) double-mutant worms show supernumerary moulting phenotypes confirming that the synthetic phenotypes are really caused by mutations of the gld-1 gene. Heterozygous gld-1(op236)/+; let-7(mg279) animals have wild-type appearance (figure 2b) consistent with gld-1(op236) behaving as a recessive allele. gld-1(op236) m+ z–; let-7(mg279) (m, maternal genotype; z, zygotic genotype) animals have a comparable phenotype with gld-1(op236) m-z–; let-7(mg279) animals (figure 2b), showing that maternal contribution of gld-1 does not affect the supernumerary moulting phenotype. To extend our analysis, we investigated possible genetic interactions of gld-1(op236) with the remaining let-7 family members mir-48, mir-84 and mir-241. Forty-two per cent (n = 43) of mir-48 mir-241; mir-84 triple mutants die owing to a burst vulva during the L4 to adult transition reminiscent to the let-7(null) phenotype [44]. The penetrance of this phenotype is enhanced by gld-1(op236), with 64% (n = 81, p = 0.013 Fisher’s exact test) lethality observed in the gld-1(op236); mir-48 mir-241; mir-84 quadruple mutant. gld-1(op236) did not affect levels of mature let-7 miRNA, thereby ruling out the possibility that GLD-1 has an essential, non-redundant role in miRNA processing (see electronic supplementary material, figure S2). Our results show that gld-1 can genetically interact with the let-7 miRNA family during somatic development when the let-7 miRNA pathway is sensitized through mutations of the let-7 family miRNAs.

4.4. gld-1(op236) affects let-7 regulation of hypodermal development

In order to better understand the extent of genetic interactions between gld-1 and the let-7 miRNA, we focused on the role of let-7 miRNA in hypodermal development. During the L4 to adult transition, let-7 downregulates lin-41, a TRM-NHL domain protein that keeps the transcription factor LIN-29 in an inactive state possibly through mRNA regulation as described for mammalian systems [45]. LIN-29 transcriptionally activates adult-stage-specific genes such as collagen col-19 [46]. Either lack of let-7 or disrupted let-7 function, causes loss of col-19 expression owing to increased LIN-29 expression that leads to reduced LIN-29 activity (figure 3a)
A transcriptional reporter expressing GFP under the control of the col-19 promoter reveals that both gld-1(op236) and let-7(mg279) single mutants have unaltered col-19::GFP expression (figure 3b). Interestingly, only 28% of gld-1(op236); let-7(mg279) double-mutant animals have wild-type levels of transgene expression (figure 3b) and 47% of double-mutant animals do not express col-19::GFP in the hypodermal hyp7 cells (figure 3d). col-19::GFP expression is not affected in gld-1(op236)/++; let-7(mg279) (1.5%; n = 66) again indicating recessiveness of gld-1(op236). Conversely, reduced expression (60.5%; n = 114) in gld-1(op236); gld-1(q485); let-7(mg279) strains indicates that the phenotype is due to a mutation of gld-1.

At the end of the L4 larval moult, lateral seam cells fuse and form extracellular structures called alae [47]. The timing of seam cell fusion and alae formation is controlled by let-7 family miRNAs [43]. Similarly, mutations in C. elegans genes encoding AGO (alg-1, alg-2) and GW182 proteins (ain-1, ain-2) also have seam cell fusion and alae formation defects [18,38]. We assayed seam cell fusion using the AJM-1::GFP junction marker as indicated (figure 3f). Analysis of differential interference contrast (DIC) images and the AJM-1::GFP junction marker indicate defects in alae formation and seam cell fusions in gld-1(op236), let-7(mg279) and gld-1(op236); let-7(mg279) animals (figure 3e). We next quantified the extent of seam cell fusion defects and found that the incidence of seam cell fusion defects is higher in gld-1(op236); let-7(mg279) double-mutant animals than in single mutants (figure 3e). In summary, our combined data suggest that gld-1 affects hypodermal development in let-7 mutant background, either by acting through let-7 or through a parallel pathway.

4.5 GLD-1 affects let-60 signalling

To check whether the genetic interactions of gld-1 with the let-7 miRNA family are restricted to the hypodermal development, we looked into the let-60/RAS pathway that functions during vulva formation [48]. mir-84 and let-7 antagonize let-60/RAS signalling in vulval precursor cells that are not destined to form the vulva. Such regulation can be assessed in vivo using let-60/RAS gain-of-function alleles that induce
ectopic vulva formation by triggering excessive MAP kinase signalling. The system is sensitized by maintaining the \textit{let-60(n1046)} gain-of-function allele in a heterozygous state or switching \textit{let-60(ga89)} temperature-sensitive gain-of-function allele from 20 to 25°C. \textit{gld-1(op236); let-60(n1046)\(\textit{+}\)} (figure 4a) and \textit{gld-1(op236); let-60(ga89)} (figure 4b) double mutants have an increased incidence of forming multiple vulvae, indicating that GLD-1 also affects vulva induction.

4.6. Germline expression of \textit{gld-1} is not necessary for somatic phenotypes

GLD-1 protein expression has previously been reported in the germline [7]. We therefore wished to determine whether \textit{gld-1} expression also occurs in somatic tissues, and whether the genetic interactions we observe during somatic development depend on a germline. To determine whether a germline is required for seam cell fusion defects in \textit{gld-1(op236)} and \textit{gld-1(op236); let-7(mg279)} animals, we used RNAi to inactivate \textit{glp-1}, which is essential for germline development [49]. We observed that the defective seam cell fusion phenotype occurs to a similar extent in animals lacking a germline as in those with a germline (figure 3c). Furthermore, somatic expression of an mCherry::H2B transcriptional reporter (the histone fusion used to focus diffuse, low level cytoplasmic GFP expression to the nucleus) under the control of the \textit{gld-1} promoter and the \textit{gld-1 3’UTR} was mainly localized to the head, tail and ventral side of the animals (see electronic supplementary material, figure S3). DIC microscopy analysis indicates that most of the positive cells are neuronal cells in the head and tail ganglia and the ventral nerve cord. Interestingly, \textit{let-7} and at least one \textit{let-7} target, \textit{hbl-1}, is also reported to have a similar expression pattern [50], although it is not known to what extent \textit{let-7} miRNA phenotypes require hypodermal or neuronal expression. It is likely that high levels of background fluorescence masked low levels of \textit{gld-1} reporter expression in other cell types. We could not confirm this localization pattern by antibody staining owing to background problems. However, we generated transgenic animals expressing full-length \textit{gld-1} fused to histone-GFP by an operon linker, generated by single copy insertion using the MosSCI technique [29,51,52]. This transgene shows the same pattern of somatic expression, shows expression in embryos and rescues \textit{gld-1(null)} in the germline (electronic supplementary material, figure S4). Even though these reporter constructs might not exactly represent endogenous GLD-1 expression, together with our genetic results, they suggest somatic roles for \textit{gld-1}.

4.7. Overexpressing a \textit{lin-41 3’UTR} construct acts as a ‘sponge’ to sequester \textit{let-7} miRNA and provides a sensitized system to assay GLD-1 activity

One of the targets of \textit{let-7} miRNA during larval development is the \textit{lin-41} miRNA [45]. Hypodermal defects in \textit{gld-1(op236); let-7(mg279)} could be the result of mis-regulation of \textit{lin-41} miRNA. To investigate this possibility, we generated a single copy MosSCI insertion of GFP::\textit{lin-41 3’UTR} fusion construct under the control of the \textit{col-10} promoter that ensures expression in hypodermal tissues. We did not observe any phenotype (figure 5a) in wild-type or in \textit{gld-1(op236)} animals. However, \textit{let-7(mg279)} mutants showed a low penetrance bursting through the vulva phenotype reminiscent to \textit{let-7(null)} phenotype (figure 5a). We likened this observation to a sponge-like effect of the GFP::\textit{lin-41 3’UTR} towards \textit{let-7} miRNA. miRNA sponges are complementary target sequences that can sequester the miRNA from its endogenous target [53]. In \textit{C. elegans}, such a sponge was used for the \textit{lin-4} miRNA [54]. The penetrance of the vulva-bursting phenotype is dramatically enhanced in \textit{gld-1(op236); let-7(mg279)} double mutants...
expressing the GFP::lin-41 3' UTR (let-7 sponge) (figure 5a). Thus, gld-1(op236) specifically enhances the let-7-dependent phenotypes, and the extent of genetic interactions between gld-1 and the let-7 miRNA pathway becomes more evident when the let-7 miRNA pathway is further compromised. Expression of a let-7 sponge with a deletion of the 3 let-7 binding sites or expression of the unrelated unc-54 3' UTR did not cause any bursting phenotype in let-7(mg279) and in gld-1(op236); let-7(mg279) animals supporting the specificity of the let-7 sponge and the interactions between gld-1 and let-7 miRNA (figure 5a).

We next expressed gld-1 under the control of the col-10 promoter in the hypodermis to investigate whether such expression of gld-1 might cause any phenotype associated with the loss of let-7 targets. col-10::GLD-1 expression in the hypodermis caused a loss of adult-stage alae (figure 5b) and a dumpy phenotype (shortened size; figure 5c,d). A dumpy phenotype also occurs following mutation of let-7 targets such as lin-41 [45]. Co-expression of the let-7 sponge partially rescues the dumpy and loss of alae phenotypes (figure 5b–d). Based on these results, we cannot exclude the possibility that gld-1 and let-7 miRNA function in parallel pathways during the hypodermal development. Equally, GLD-1 expression in the hypodermis might cause unrelated phenotypes. However, another likely interpretation of these experiments is that GLD-1 and let-7 act in conjunction to excessively repress target mRNAs possibly in the same pathway, and that reducing the ‘dose’ of let-7 using the sponge alleviates target gene repression.

4.8. SILAC in nematodes identifies proteome wide changes in gld-1 and let-7 mutants

Our results suggest that GLD-1 and let-7 synergistically affect animal development. We wanted to determine whether the
phenotypes we observed are due to the mis-regulation of either a single or small number of genes, as opposed to affecting multiple target genes. In addition, we wanted to determine whether GLD-1 and the let-7 miRNA regulate distinct or same targets. To address this question, we used nematode SILAC to systematically quantify protein levels [34,36]. The strongest genetic interaction between gld-1 and let-7 occurs in the let-7 sponge system (figure 5a). Thus, to assess changes in the proteome of the respective strains, we used the following experimental set-up. For the SILAC experiment synchronized L1 larvae of three strains, namely (A) [let-7 sponge], (B) let-7[mg279]; [let-7 sponge] and (C) gld-1(op236); let-7[mg279]; [let-7 sponge] were grown up to the young-adult stage until the bursting phenotype just becomes visible and subjected to quantitative mass spectrometry (figure 6a). As the animals expressing let-7 sponge alone do not display any phenotype, we considered them as the baseline similar to using wild-type. Thus, by comparing the animals with a weak phenotype (B) to animals with a strong phenotype (C), we aimed to identify proteins whose expression change might be responsible for the bursting through the vulva phenotype and help explain the interaction between gld-1 and the let-7 miRNA. In a SILAC experiment, the relative ratios of two sets of proteins can be measured by differential isotope labelling. We then determined proteins differentially expressed when B was compared with A. At the same time, we also determined differentially expressed proteins comparing C with A. As a control, we analysed the levels of GFP expression under the control of lin-41 3’UTR sponge by Western blotting. GFP levels are higher in the let-7 sponge animals, compared with the let-7 sponge only (B to A; electronic supplementary material, figure S5a). We identified a similar rise in GFP levels in let-7 sponge animals, compared with the let-7 sponge only (B to A; electronic supplementary material, figure S5b). We identified a similar rise in GFP levels in SILAC experiments, and the level of GFP was further increased in gld-1(op236); let-7[mg279]; let-7 sponge animals (C to A; electronic supplementary material, figure S5b). This result confirms the sensitivity of our SILAC-based approach. In the B/A comparison, 2708 proteins passed our specificity criteria, whereas 2927 passed in the C/A comparison (see Materials and methods). We focused on comparing the abundance of the 2179 proteins that were reliably detected in both datasets. The ratios of (C) gld-1[op236]; let-7[mg279]; [let-7 sponge] protein to (A) [let-7 sponge] protein shown on the y-axis are compared with the (B) let-7[mg279]; [let-7 sponge], with (A) [let-7 sponge] ratios depicted on the x-axis (figure 6a).

Among these 2179 proteins, 252 overlap with the 1084 previously described GLD-1 targets (figure 6a, coloured in blue) [55,56]. Proteins (239) overlap with 1322 predicted let-7 targets (figure 6a, coloured in red, mirWIP database [57]). Fifty-four proteins are predicted to be both GLD-1 and let-7 targets (purple spots above the 1.2-fold line). Empty vector RNAi were grown up to the young-adult stage until the early larval lethality in these animals (RNAi is done in the same strain). We picked six genes upregulated more than twofold and are GLD-1 or predicted let-7 targets ( purple spots above the 1.2-fold line). Solid black and grey lines indicate 1.2-fold and two-fold thresholds, respectively. Dots represent 2179 proteins. Among them GLD-1 targets [55,56] are coloured blue, mirWIP database let-7 targets predictions [57] are coloured red, and the possible GLD-1 and let-7 co-targets based on these lists are coloured purple. The remaining proteins are coloured in grey. CDL-1, DNJ-2 and B0303.3 are possible GLD-1 and let-7 targets ( purple spots above the twofold line) and are GLD-1 or predicted let-7 targets alone. Solid black and grey lines indicate 1.2-fold and two-fold thresholds, respectively. Dots represent 2179 proteins. Among them GLD-1 targets [55,56] are coloured blue, mirWIP database let-7 targets predictions [57] are coloured red, and the possible GLD-1 and let-7 co-targets based on these lists are coloured purple. The remaining proteins are coloured in grey. CDL-1, DNJ-2 and B0303.3 are possible GLD-1 and let-7 targets that are upregulated more than 1.2-fold (arrows). (b) RNAi-mediated knockdown of 9 genes upregulated in the gld-1[op236]; let-7[mg279]; [let-7 sponge] animals (RNAi is done in the same strain). We picked six genes upregulated more than twofold and are GLD-1 or predicted let-7 targets (red and blue spots above the twofold line) and three genes upregulated more than 1.2-fold that are GLD-1 and predicted let-7 targets (purple spots above the 1.2-fold line). Empty vector RNAi and GFP RNAi are used as negative and positive controls respectively. B0303.3 RNAi results are omitted due to the early larval lethality in these animals (error bars = s.e.m. of triplicate, p-values calculated using Fisher’s exact test).

Figure 6. SILAC-based proteomics in let-7 and gld-1 mutants. (a) log2 relative abundances of 2179 proteins in let-7[mg279]; [let-7 sponge] (x-axis) and gld-1[op236]; let-7[mg279]; [let-7 sponge] (y-axis) animals compared with [let-7 sponge] animals alone. Solid black and grey lines indicate 1.2-fold and two-fold thresholds, respectively. Dots represent 2179 proteins. Among them GLD-1 targets [55,56] are coloured blue, mirWIP database let-7 target predictions [57] are coloured red, and the possible GLD-1 and let-7 co-targets based on these lists are coloured purple. The remaining proteins are coloured in grey. CDL-1, DNJ-2 and B0303.3 are possible GLD-1 and let-7 targets that are upregulated more than 1.2-fold (arrows). (b) RNAi-mediated knockdown of 9 genes upregulated in the gld-1[op236]; let-7[mg279]; [let-7 sponge] animals (RNAi is done in the same strain). We picked six genes upregulated more than twofold and are GLD-1 or predicted let-7 targets (red and blue spots above the twofold line) and three genes upregulated more than 1.2-fold that are GLD-1 and predicted let-7 targets (purple spots above the 1.2-fold line). Empty vector RNAi and GFP RNAi are used as negative and positive controls respectively. B0303.3 RNAi results are omitted due to the early larval lethality in these animals (error bars = s.e.m. of triplicate, p-values calculated using Fisher’s exact test).

We tested whether the depletion of these three proteins suppresses the vulva-bursting phenotype of the gld-1[op236]; let-7[mg279]; [let-7 sponge] strain (figure 6b). Targeting the [let-7 sponge] which is co-lab-10::GFP:lin-41 3’UTR reconstructs GFP RNAi lead to a complete suppression of the vulva-bursting phenotype and thus served as a positive control. The depletion of one of the candidates, namely cdl-1 lead to a reduced vulva-bursting phenotype consistent with the notion that the upregulation of CDL-1 in the gld-1[op236]; let-7[mg279] background might contribute to the vulva-bursting phenotype. Indeed, cdl-1 3’UTR harbours a GLD-1 and a let-7 binding site (electronic supplementary material, figure S7). CDL-1 is a histone mRNA hairpin binding protein required for expression of histones [58–61]. It is expressed in all somatic cells with strong expression in proliferating cells such as hypodermal cells, intestinal cells and the germ cells [59]. CDL-1 is required for larval development and affects vulva morphology [59,61]. However, the suppression of the vulva-bursting phenotype by CDL-1 RNAi in gld-1[op236]; let-7[mg279]; [let-7 sponge] animals is not complete. This indicates that other factors also contribute to the vulva-bursting phenotype.
4.9. Identification of GLD-1-containing complexes

Our data are consistent with GLD-1 either directly or indirectly interacting with the miRNA pathway. To investigate this genetic interaction at biochemical level, we next aimed to purify proteins that interact with GLD-1. We used GLD-1 antibodies to immunoprecipitate GLD-1 complexes in wild-type animals and used mass spectrometry to identify GLD-1 interactors. To verify the specificity of GLD-1 interactions, we also pulled down GLD-1 using a GFP-binder from animals expressing a GLD-1::GFP fusion protein and focused our subsequent analysis on proteins specifically pulled down in both purification approaches (figure 7a).

Among the GLD-1 interactors identified, many are associated with RNA and some are involved in RNA-mediated gene regulation (figure 7a). We identified the CGH-1 helicase, CAR-1 and the Y-box domain proteins CEY-2, CEY-3 and CEY-4, all previously reported to be components of a complex localized to RNP granules in the *C. elegans* germline, and that are likely to function in translational repression [62]. Importantly, CGH-1 is proposed to act in miRNA-mediated gene expression. Depletion of cgh-1 enhances the defects of let-7 family mutants and CGH-1 biochemically interacts with ALG-1, AIN-1 and NHL-2 [5]. Indeed, ALG-1 also co-purified with GLD-1 in our experiments (figure 7b). Other proteins identified as GLD-1 interactors include PAB-1 and SQD-1. PAB-1 is a *C. elegans* poly(A) binding protein and also a component of AIN-1, AIN-2 and CGH-1 complexes, suggesting a role in translational regulation and miRNA-mediated repression [18,63,64]. SQD-1 is the *C. elegans* orthologue of the *Drosophila* squid hnRNP protein, previously identified as an AIN-2 and mir-35 miRNA-associated protein [18,65]. PAB-1, CGH-1, CAR-1, CEY-1-4 and SQD-1 were also identified as GLD-1 protein interactors in a recent study [66]. In the same study, interaction of CGH-1 with GLD-1 was shown to depend on the presence of RNA. Considering all the GLD-1 interactors have RNA-binding domains, the presence of RNA might be essential in all these interactions. In summary, GLD-1 interactors identified in this and previous studies associate with proteins known or suspected to be involved in miRNA-mediated gene repression.

We next investigated whether GLD-1 interactors affect let-7 miRNA function similar to GLD-1. We therefore assessed the extent of vulva-bursting upon RNAi of those interactors in *let-7* sponge and *let-7* (mg279); *let-7* sponge animals. RNAi against *alg-1*, *ain-1* and *ain-2*, core miRNA components, were used as positive controls. As expected, *alg-1* RNAi induces a strong vulva-bursting phenotype in both *let-7* sponge and *let-7* (mg279); *let-7* sponge animals (figure 7b). *ain-1* and *ain-2* RNAi induced the vulva-bursting phenotype only in the sensitive *let-7* (mg279); *let-7* sponge animals. Among the GLD-1 interactors besides *alg-1* RNAi, cgh-1 and pab-1 RNAi also induced a strong vulva-bursting phenotype in the *let-7* (mg279); *let-7* sponge animals, supporting their role in miRNA function.

5. Discussion

The starting point of our work was the identification of two miRNA effector genes, *vig-1* and *nhl-2* as genetic enhancers of *gld-1* (op236) (figure 1). Both genes had previously been shown to affect miRNA function [4,5], although not in the germline. It is possible that the germline phenotypes we observed are related to a miRNA-associated function, although it is equally likely that VIG-1 and NHL-2 may, either directly or indirectly, affect GLD-1 function, or else may act in conjunction with GLD-1 to mediate translational repression of GLD-1 targets in the germline. Different phenotypes observed in the *gld-1* (op236); *vig-1*(ok2536) and the *gld-1* (op236); *nhd-2* (ok818) double mutants suggest that *vig-1* and *nhd-2* function in different pathways in the germline. We will investigate these possibilities in future studies.

Intrigued by the genetic interactions with those miRNA effector genes, we investigated possible roles of *gld-1* in multiple miRNA-mediated pathways and uncovered novel roles for *gld-1* during the somatic development of *C. elegans*. Given that *gld-1* phenotypes and expression were previously only described for the germline, we were surprised to find GLD-1 phenotypes associated with somatic development. Enhancement of *mir-35* family embryonic and larval lethal phenotypes may be explained by perturbation of maternal miRNA pools derived from *gld-1* (op236) germlines that may enhance *mir-35* phenotypes. However, it is unlikely that such a model can explain the genetic interactions we observed between *gld-1* and *let-7* family miRNAs. *let-7*-related

<table>
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<th>protein names</th>
<th>total peptide (background peptides)</th>
<th>% mean coverage protein size (kD)</th>
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<td>20 (1)</td>
<td>19.4</td>
</tr>
<tr>
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<td>13 (2)</td>
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<tr>
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<td>6 (1)</td>
<td>10.2</td>
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interactors we identified (figure 7): ALG-1 is a core component of miRNAs and also by the target genes whose mis-regulation is explained by the robustness and redundancy of the miRNA pathway becomes apparent. This finding can be explained by the hypomorphic let-7(mg279) mutants, endogenous targets are not efficiently dealt with when the let-7 sponge is present (figure 5a). Only in this ‘very sensitive’ situation, a role for gld-1 in the let-7 miRNA pathway becomes apparent. This finding can be explained by the hypomorphic let-7(mg279) mutants, endogenous targets are not efficiently dealt with when the let-7 sponge is present (figure 5a).

We focused on the let-7 miRNA pathway, whose components have been much more characterized in C. elegans. By using already established tools, we could show that gld-1 affects multiple let-7 miRNA regulated pathways (figures 2–4). Importantly, we generated a sensitized system using a let-7 sponge and showed that gld-1(qp236) specifically enhances let-7 loss-of-function phenotypes (figure 5). Our let-7 sponge system confirms the notion that the miRNA pathways are highly redundant. let-7 miRNA levels in wild-type animals are sufficient to regulate both the endogenous targets and also an additional transgene target (let-7 sponge). However, when the let-7 miRNA levels are limiting, such as in the hypomorphic let-7(mg279) mutants, endogenous targets are not efficiently dealt with when the let-7 sponge is present (figure 5a).

Overall, we suggest two possible mechanisms for GLD-1 and miRNA interactions that are not mutually exclusive and may act in parallel. First, mutation of both GLD-1 and miRNAs could mis-regulate several targets within a single pathway, leading to the observed phenotypes. For instance, moulting defects in let-7 mutants are partly due to mis-regulation of the nuclear hormone receptors nhr-23 and nhr-25 [41], and nhr-23 is a predicted GLD-1 target [55,56]. We could not detect NHR-23 in our SILAC experiments. Similarly, some of the phenotypes we observed (figure 5b) might be explained by negative regulation of LIN-28 by GLD-1 as it was reported for the germline [55]. However, we did not detect changes in LIN-28 protein levels, which is why we did not follow up on this lead.

A second possibility is that GLD-1 and miRNAs may co-regulate a subset of miRNAs. The interactions we observed between GLD-1, CGH-1, PAB-1 and ALG-1 in GLD-1 complexes support such a mechanism. Consistent with this model, GLD-1 appears to associate with several 3'UTRs that are known or predicted miRNA targets in C. elegans. For example, the potential mir-35 targets, lin-23 and gld-1 [69], have also been identified as GLD-1 targets [55]. Similarly, lin-28 and ztf-7 are let-7 miRNA targets [70,71] and these genes have also been identified as GLD-1 targets [55].

We are aware that biochemical interactions reflect total animal extracts and that most GLD-1 protein expression is likely to occur in the germline. Thus, the association of GLD-1 with 3'UTRs in somatic cells may be underrepresented in biochemical experiments aimed to determine GLD-1 targets [55]. GLD-1 has been extensively studied in the germline and consensus-binding motifs have been defined [55,72]. We also know that GLD-1 appears to bind RNA as a dimer and that GLD-1 RNA binding is enhanced when multiple binding sites are available [72]. Still, we know next to nothing regarding how GLD-1 actually confers translational repression. It is intriguing that several proteins previously associated with miRNA regulation biochemically interact with GLD-1. CGH-1 interacts with the miRISC complex and GLD-1 in an RNA-dependent manner [5,66], and therefore raises the possibility of being the mediator between the two translational repression mechanisms. In a recent study, one of the C. elegans poly(A) binding proteins, PABP-2, was shown to antagonize let-7 miRNA function [73]. In our study, we show that PAB-1 is required for proper let-7 function and this is in line with the interactions between PAB-1 and AIN-1 [63]. These results indicate that different poly(A) binding proteins may affect miRNA function in opposite ways and perhaps these effects depend on other RNA-binding proteins like GLD-1. We therefore speculate that the mechanisms of GLD-1-mediated translational repression and miRNA-mediated translational repression may overlap. It will be interesting to investigate this potentially-shared mechanism in the future.
a role for QKI in tumour suppression [75]. In a more recent study, two QKI isoforms were shown to regulate miR-7 expression in glial cells [76]. Studying the interactions between GLD-1 and miRNA-mediated gene regulation can thus reveal important regulatory interactions occurring during animal development.

Acknowledgements. We are grateful to Gyorgy Hutvagner and Sarah Bajan for their assistance in miRNA-related work; Peter Sarkies for his valuable suggestions on mass-spectrometric data analysis and usage of R; to the members of the Gartner Laboratory for discussions and critical comments; and Sara ten Have and the proteomics support team for help with the mass spectrometry analysis. We thank Gary Ruvkun for sharing the let-7/miR-279 strain, Ralf Ciok for supporting J.E.W., and the Caenorhabditis Genetics Centre for supplying most of the parental strains.

Funding statement. Research in the Gartner Laboratory was supported by a Wellcome Trust programme grant, a CR-UK Career Development Award (C11852/A4500) and a Wellcome Trust project grant (081923/Z/07/Z). N.J.L. and E.A.M. were supported by a CR-UK programme grant (C13474/A11832). A.G. is a Wellcome Trust Senior Research Fellow. A.I.L. is a Wellcome Trust Principal Research Fellow. The Wellcome Trust grant no. 097045/B/11/Z provided infrastructure support.

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