Dietary restriction (DR) increases life span through adaptive changes in gene expression. To understand more about these changes, we analyzed the transcriptome and translatome of Caenorhabditis elegans subjected to DR. Transcription of muscle regulatory and structural genes increased, whereas increased expression of amino acid metabolism and neuropeptide signaling genes was controlled at the level of translation. Evaluation of posttranscriptional regulation identified putative roles for RNA-binding proteins, RNA editing, miRNA, alternative splicing, and nonsense-mediated decay in response to nutrient limitation. Using RNA interference, we discovered several differentially expressed genes that regulate life span. We also found a compensatory role for translational regulation, which offsets dampened expression of a large subset of transcriptionally down-regulated genes. Furthermore, 3' UTR editing and intron retention increase under DR and correlate with diminished translation, whereas trans-spliced genes are refractory to reduced translation efficiency compared with messages with the native 5' UTR. Finally, we find that smg-6 and smg-7, which are genes governing selection and turnover of nonsense-mediated decay targets, are required for increased life span under DR.

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Introduction

Methods of dietary restriction (DR) that increase life span involve restricting nutrients without causing malnutrition. Many forms of DR exist, including restriction of calories, specific macronutrients or micronutrients, and the timing of access to food (Greer and Brunet, 2009; Honjoh et al, 2009). Along with extended longevity, DR increases resistance to stress and improves other parameters of health from yeast to mammals (Mair and Dillin, 2008,4). Changes in transcription associated with DR are among the adaptive changes in response to DR (Vellai et al, 2003; Apfeld, 2004). Highly conserved pathways shown to have roles in increased life span under DR include the insulin/insulin-like signaling (ILS) and mechanistic target of rapamycin (TOR) pathways. In response to changes in nutrient availability, the ILS pathways modulate cellular processes and coordinate responses in different tissues through hormone signaling (Lin et al, 2001), whereas the TOR pathway can modulate cellular responses by directly sensing nutrients within the cell (Rohde et al, 2001). Changes in transcription associated with these pathways has been pivotal in resolving connections between individual transcripts and corresponding proteins from yeast to humans (Ghaemmaghami et al, 2003; de Godoy et al, 2008; Schwanhausser et al, 2011; Wilhelm et al, 2014). Thus, a comprehensive understanding of gene expression remodeling that takes place under DR requires an approach that accounts for transcript abundance and the efficiency with which individual transcripts are used to synthesize new protein. This approach provides the basis for development of hypotheses and tests of mechanisms that control gene expression at different levels. For example, it allows for the identification of putative sequence motifs within mRNA (i.e., cis-regulatory elements) and corresponding miRNAs and RNA-binding proteins (RBPs) (i.e., trans-acting factors) targeting these motifs to ascertain their roles in translational control.
Today, methods involving polysome profiling (Zong et al, 1999) and ribosome footprinting (Ingolia et al, 2009) provide information that can be used to help distinguish forms of posttranscriptional regulation. By isolating mRNA that is associated with actively translating ribosomes, polysome profiling allows the translation state of individual transcripts to be quantified between treatments. In comparison, ribosome footprinting allows for the distribution of the ribosome along mRNA to be quantified by sequencing only the regions of transcripts protected from nuclease digestion by bound ribosomes. These technologies have been applied in yeast to characterize the role of 5’ UTRs in transcript stability and translatability (Ringnér & Krogh, 2005), to pinpoint exonic polymorphisms in mRNA that affect translation, and to analyze stress-induced changes in translation of specific transcripts (Lackner et al, 2012). Polysome profiling and ribosome footprinting have also been used to consider isoform-specific translational regulation (Sternert-Weiler et al, 2013) and to assess selective mRNA translation during mechanistic TOR inhibition in cell culture (Ölschen et al, 2013). These studies and others like them have started to resolve the importance of posttranscriptional mechanisms in regulating gene expression. However, there is still a paucity of information on the relationships that exist between genes controlled transcriptionally, translationally, or both in mediating the adaptive response to DR. Understanding these relationships is key to understanding how DR promotes healthy aging.

In the following study, Caenorhabditis elegans adult nematodes were subjected to a form of DR involving food dilution that results in robust life span increase (Chen et al, 2009). Subsequently, animals were assessed for gene expression changes according to total and polysome-associated mRNA to differentiate transcriptional and posttranscriptional inputs. mRNAs differentially associated with polysomes under DR were investigated in silico for characteristics that could explain changes in gene expression at this level. Genes transcriptionally and/or translationally down-regulated under DR were screened using RNAi for effects on life span under fully fed conditions. Results reveal novel genes and connections with forms of posttranscriptional regulation important for increased life span under DR.

Results

Transcriptional responses to DR implicate muscle and metabolic adaptation

Using food dilution (Chen et al, 2009) to impose DR starting at day 1 of adulthood extended median life span of C. elegans by ~40% (Fig 1A). To better understand the different inputs to gene expression, we analyzed total and translated (i.e., polysome-associated) mRNA after 4 d under DR or fully fed (ad libitum, or AL) conditions in adult nematodes. Using four biological replicates, total and translated mRNA from AL and DR worms were analyzed by next-generation sequencing (Fig 1B). In brief, 100 bp paired end reads were aligned to the C. elegans genome and reads were counted using HTSeq (Fig 1C). edgeR was used to normalize the dataset and filter out lowly expressed mRNA that could not be reliably quantified (see the Materials and Methods section), leaving 8,301 annotated coding genes in the analysis of differential expression. A heatmap representing expression across this dataset demonstrated that the biological replicates clustered together, that the expression dataset was normally distributed, and that several instances of differential expression existed between different groups (Fig S1A).

To compare total mRNA expression between AL and DR conditions, we identified genes that were significantly changed twofold or more between diets (false discovery rate [FDR] < 0.05; Fig 1D). Of these, 257 were up-regulated under DR and 782 were down-regulated (Table S1). Gene ontological (GO) analysis was then used to determine whether particular biological processes were represented among differentially expressed genes. Up-regulated genes were enriched for processes related to myosin and myofibril assembly, muscle contraction, locomotion, oxidation/reduction, and ion transport (Fig 1E and Table S2), whereas down-regulated genes were enriched for biological processes related to apoptosis, amino acid metabolism, defense response, epigenetic regulation, RNA metabolism, and transcription (Fig 1F and Table S2).

Among the up-regulated genes, expressions of several genes are known to be critical for age-related health and longevity. Like age-related sarcopenia in humans, locomotion and the ability to transduce force generated by muscles is lost with age in C. elegans (Hahm et al, 2015; Rollins et al, 2017). Under DR, the genes encoding thick filaments (unc-54 and myo-1) and movement-coordinating troponins (pat-10, tni-3, and tnt-4) of muscle sarcomeres were upregulated (Table S2), suggesting that they may be involved in the maintenance of locomotion with age in DR restricted animals. In line with this, C. elegans mutants with defective unc-54 activity have reduced capacity to generate movement force (Várkuti et al, 2012). In addition, overexpression of pat-10 leads to increased actin filament stability, resistance to protein unfolding stress, and life span (Baird et al, 2014). Among the genes with roles in oxidation reduction were members of the cytochrome P450 family (cyp-34A9, cyp-3SA2, cyp-3SC3, and cyp-34A4). Cytochrome P450 isozymes can serve in the metabolism of xenobiotics and other toxins (Ding & Kaminsky, 2003; Lindblom & Dodd, 2006), which might otherwise impinge on longevity.

Defense response genes were down-regulated, including those encoding neuropeptide antimicrobials (e.g., npl-29 and npl-31) in addition to tol-1, the only Toll-like receptor in C. elegans. Although efficacy of defense responses is usually improved in DR animals, diminished expression of these genes may be because of reduced microbe sensing resulting from the form of DR itself, which involves dilution of their bacterial food source. The transcription factor GO term included regulators of embryonic development, which were expected to be decreased given the negative effect of DR on reproduction. These included nuclear hormone receptors (e.g., nhr-2 and nhr-112), cyclin-dependent kinase 8 (cdk8), a homeobox factor (ceh-40), and a HAND bHLH factor important for tissue differentiation (hnd-1), among others (Table S2). The heat shock transcription factor gene hsf-1 was also down-regulated, presumably because of globally reduced protein synthesis, which requires hsf-1-dependent chaperones to direct the folding of nascent proteins.

In a previous study, transcript levels were analyzed in C. elegans subjected to DR based on intermittent fasting (Honjo et al, 2009). We compared our list of differentially regulated genes from bacterial

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dilution with those obtained by Honjoh et al (2009) using gene set enrichment analysis (GSEA, Fig S1B). This analysis demonstrated a significant (FDR < 0.001) enrichment of both up- and down-regulated genes between the two datasets despite differences in dietary regimes and quantification methods (i.e., next-generation sequencing versus microarray). To gain insight into the transcriptional differences between DR by food dilution and intermittent fasting, differentially expressed genes in common between DR methods and those unique to food dilution were subjected to GO analysis. Terms related to oxidation/reduction and muscle contraction were up-regulated in common among both forms of DR (Table S2). Among down-regulated genes, terms in common pertained to defense and immune response. However, the term “regulation of transcription” was unique to down-regulated genes in the food dilution DR dataset (Table S2). Together, results demonstrate that many of the same processes regulated transcriptionally by intermittent fasting are also regulated by food dilution in C. elegans.

To gain a better understanding of which responses to DR are species specific and which are conserved among different species, we compared our differential expression results with the meta-analysis performed by Han and Hickey (2005). In the meta-analysis, they compared differently expressed genes in mouse, rat, pig, monkey, yeast, and fly subjected to DR. Interestingly, their study showed a lack of overlap in expression changes of specific genes in common to all these species. However, GO analysis did point to the conservation of biological processes involved in adaptive responses to DR like those observed in the present study. Specifically, the meta-analysis reported the enrichment of genes annotated with the term metabolism among all animals listed. In addition, there was a high level of overlap for terms related to stress/immune response and regulation of transcription that were the same or similar in C. elegans (Fig 1F). These similarities imply evolutionary conservation of transcriptional responses to DR at the level of biological processes.

**Translation frequently offsets transcriptional down-regulation under DR**

To differentiate transcriptional and translational regulation of gene expression, we analyzed the relative abundance of the 8,301 quantified genes within the total and polysome-associated mRNA pools. Under AL conditions, 82% of genes had similar abundance...
between pools. The remaining 18% showed a twofold or greater difference between pools and were considered to be translationally regulated (Fig 2A). Thus, genes with greater relative abundance among polysomes than total mRNA were considered to be translationally promoted, whereas those with reduced polysomal association were considered translationally suppressed. In contrast to AL conditions, 34% of genes were translationally regulated under DR (Fig 2B). This is reflected by reduced correlation between total and translated mRNA pools (r = 0.88 for AL versus 0.83 for DR, P < 0.0001, t test of Fisher r-z transformed coefficients). In addition,
the distribution of changes in gene expression between the total and translated fractions was significantly different under DR compared with AL ($P < 2.2 \times 10^{-16}$, two-sample Kolmogorov–Smirnov test, Fig 2C). As seen in the Venn diagram inset in Fig 2C, the majority of selectively translated genes under AL were also subject to translational regulation under DR. Thus, a common set of genes are translationally regulated under both conditions, whereas an additional set of genes becomes translationally regulated under DR.

To characterize the predominant modes of gene regulation that occur under DR without bias, we clustered genes that only become translationally regulated under DR (1,665 in all, see Venn diagram in Fig 2C) into groups with similar expression profiles. Partitioning around medoids was used to cluster genes into the optimal number of groups using the gap statistic (Tibshirani et al, 2001). These genes were optimally clustered into three groups as seen in a principle component analysis plot that explained 97.6% of the dataset variance (Fig S2A). The relative expressions of all 1,665 genes for total and translated mRNA under AL and DR are shown for each of the three clusters in Fig S2B-D. The first cluster consisted of 530 genes exhibiting down-regulated transcript levels under DR that were partly offset by positive selective translation (Fig S2B). The second group contained 492 genes lacking transcriptional changes with modest negative translation changes under AL that became more negative under DR (Fig S2C). The third cluster contained 643 genes that were essentially unchanged translationally under both conditions but that become translationally promoted under DR (Fig S2D). Although other modes of regulation exist under DR, these clusters account for the majority of expression changes. Thus, it appears that there are three fundamental roles of translational regulation that occur under this DR regimen: to oppose transcriptional down regulation (cluster 1), to reinforce translational suppression tendency observed under AL (cluster 2), and to increase expression during DR in the absence of transcriptional changes (cluster 3).

The analysis in Fig S2 helps resolve patterns of expression for genes that only become translationally regulated subsequent to DR. To determine which genes exhibit net translation changes between conditions, we devised the Differential Polysome Association Ratio (DPAR). This is calculated by taking the ratio of translated to total mRNA under DR and dividing by the same ratio under AL for a given gene. It should be noted that, while global translation rates are lower under DR, DPAR is only influenced by relative changes in the distribution of specific mRNAs within polysomes and total mRNA. A significant (FDR < 0.5) twofold or greater change in translation was observed for 482 translationally promoted genes and 116 translationally suppressed genes (Fig 2D and Table S3). A threshold of twofold change in polysome association was used to focus the analysis on genes experiencing large changes in translational regulation and comes with the tradeoff of potentially missing smaller but still biologically relevant regulation. Interestingly, the tendency for translationally changed genes to be up-regulated under DR was opposite of the tendency for transcriptionally changed genes, which were much more frequently down-regulated (compare Figs 1D and 2D). This led us to investigate how often translation offsets transcriptional regulation under DR. Of the genes that were translationally promoted under DR, 58% lacked significant transcript level changes and 40% had significantly decreased transcript level changes, leaving very few genes that were both transcriptionally and translationally promoted (Fig 2E). Given that only 12.5% of quantifiable genes in our dataset displayed significant transcriptional regulation, the fact that 33% of translationally promoted genes were significantly down-regulated at the transcript level was, itself, significant ($P < 2.2 \times 10^{-16}$, Fisher’s exact test). Conversely, 90% of translationally down-regulated genes showed no change in transcription. The frequent opposition between translation and transcription may help explain numerous studies showing disparate results between gene transcription and protein expression (Ghaemmaghami et al, 2003; Schwanhäusser et al, 2011; Wilhelm et al, 2014).

**Translational adaptation to DR involves down-regulating anabolic processes and altering amino acid metabolism and neuropeptide signaling**

We performed GO enrichment analysis of DPAR genes to determine which biological processes are candidates for DR-relevant adaptation through translation. Translationally promoted DPAR genes were enriched ($P > 0.05$) for processes related to amino acid metabolism, neuropeptide signaling, abiotic responses, and determination of adult life span (Fig 2F and Table S4). One example is gst-10, a glutathione S-transferase for which overexpression has been shown to increase median longevity in *C. elegans* by 22% (Ayyadevara et al, 2005). Interestingly, translationally promoted DPAR genes *dod-19, dod-23,* and *mtl-2* were previously shown to be down-regulated in *daf-2* ILS mutants and could further increase life span when knocked down in the *daf-2(mut150)* background (Murphy et al, 2003). In the case of *dod-19* and *dod-23*, their transcriptional down-regulation under DR (>24-fold and >5-fold reduction, respectively) was far greater than their translational promotion (eightfold and twofold increase, respectively), which is likely to result in an overall reduction in new protein synthesis of these genes under DR, consistent with their negative roles in longevity. The *mtl-2* mutant has a life span similar to wild-type worms (Hughes & Stürzenbaum, 2007), which is in line with a context-dependent role in longevity. Among the translationally suppressed genes, there was an enrichment of biological terms related to protein folding, translation, cell cycle, growth, and development (Fig 2G and Table S4). These results are in agreement with effects of DR on limiting growth and decreasing global translation.

**RNAi screen of translationally regulated genes under DR revealed novel longevity genes**

As DR prolongs longevity, we tested whether inhibiting genes that are down-regulated under food dilution increases life span in *C. elegans*. To avoid deleterious effects on growth, RNAi was initiated after development was complete. We included the top 100 transcriptionally down-regulated genes and the top 95 translationally down-regulated genes under DR using the Ahringer (Fraser et al, 2000; Kamath et al, 2003) and ORFeome (Rual et al, 2004) RNAi libraries. The genes tested are listed in Table S5.

Three of the 100 transcriptionally suppressed genes resulted in a significant extension in median life span when targeted with RNAi: *fbxb-24, sdz-33,* and *D1086.3* (Fig 2H and Table S6). The genes *fbxb-24* and *sdz-33* encode proteins containing F-boxes, which have been
implicated in mediating protein–protein interactions important for cell cycle regulation and signal transduction (Craig & Tyers, 1999).

Little information is available for D1086.3, but it is the only gene both transcriptionally and translationally down-regulated with a life span phenotype (Table S6 and Fig 2H). The list of screened genes also included dod-19, dod-23, and clec-186, which have been found in previous studies to increase life span when knocked down but which did not increase life span in the current study. dod genes are named for being downstream of DAF-16, a forkhead box O transcription factor required for increased life span when the ILS pathway is attenuated (Murphy et al, 2003). These dod genes are down-regulated when the ILS pathway is genetically restricted, and targeting them with RNAi in daf-2(mu150) animals further increases the long life span associated with background (Murphy et al, 2003). Our results indicate that these dod genes may require muted ILS to effectively increase life span when they are targeted with RNAi. Knockdown of the innate immunity gene clec-186 was shown to extend life span in C. elegans with increased sensitivity to RNAi (Hamilton et al, 2005), suggesting that the total or tissue-specific extent of suppression is a factor for its role in life span.

Seven of the 95 down-regulated DPAR genes increased life span when targeted for knockdown via RNAi, including D1086.3. The other six genes are daf-21, cct-4, cdk-2, iff-1, pab-1, and kbp-1 (Fig 2H). The daf-21 gene encodes the orthology of the mammalian molecular chaperone HSP90. Despite its title as a heat shock protein, HSP90 is a synthase, encodes for a chaperonin required for SKN-1, the innate immunity gene tenuated (Murphy et al, 2003). These factors required for increased life span when the ILS pathway is attenuated (Murphy et al, 2003). Our results indicate that these dod genes may require muted ILS to effectively increase life span when they are targeted with RNAi. Knockdown of the innate immunity gene clec-186 was shown to extend life span in C. elegans with increased sensitivity to RNAi (Hamilton et al, 2005), suggesting that the total or tissue-specific extent of suppression is a factor for its role in life span.

Trans-regulated genes for their role in life span. The 5′ UTR of many C. elegans mRNA are trans-spliced with one of a small number of short spliced leader (SL) sequences that replace much of the originally transcribed 5′ UTR. 5′ UTRs are important for regulating translational efficiency, and trans-splicing has a positive effect on translation in unspliced C. elegans (Yang et al, 2017). Commonly, the first gene in an C. elegans operon is trans-spliced to SL1, and all downstream transcripts are trans-spliced to SL2 (Allen et al, 2011). For genes that are not in operons, 5′ UTRs are frequently trans-spliced to SL1, with around 30% of transcripts retaining the native 5′ UTR (Allen et al, 2011).

Using annotations of SL1 and SL2 spliced genes from Allen et al (2011), we calculated the average fold change in translational regulation of genes with trans-spliced or native 5′ UTRs. Under AL, our analysis confirmed that both SL1 and SL2 trans-spliced messages tend to be better translated than transcripts with native 5′ UTRs (Fig 3B), as previously reported (Yang et al, 2017). DR led to translational suppression of SL1 spliced genes compared with AL conditions (P = 1.4 × 10−7, Wilcoxon rank sum test with continuity correction). In contrast, the translation efficiency of SL2 spliced genes was unchanged under DR (P = 0.11, Wilcoxon rank sum test with continuity correction). For both SL1 and SL2 genes, translation was preserved better in the transition from AL to DR compared with those annotated with native 5′ UTRs.
Approximately 73% of coding genes quantified in this study were annotated as SL1 trans-spliced (Fig 3C). In comparison, a significantly lower proportion of SL1 trans-spliced transcripts were among promoted DPAR genes (61%, $P < 0.01$, Fisher’s exact test), whereas a similar proportion was observed among repressed genes (63%, $P > 0.05$, Fisher’s exact test). A similar analysis for SL2 trans-spliced transcripts showed a significantly lower proportion among promoted DPAR genes (4%, Fig 3D and $P < 0.001$, Fisher’s exact test) but not among suppressed DPAR genes (17%, $P > 0.05$, Fisher’s exact test). Thus, while promoted DPAR genes were depleted among SL1 and SL2 transcripts, the depletion is modest and no change from the average distribution of trans-splicing was observed for repressed DPAR genes, suggesting that trans-splicing is unlikely to be a primary driver of differential translation among DPAR genes.

**DR increases 3’ UTR editing, which is associated with reduced translation**

Within the RNA-seq dataset we found a number of putative adenosine RNA editing events with the potential to alter translational regulation. The modification of adenosine to inosine (A-to-I) is the most prevalent type of RNA editing in many species and is catalyzed by action of adenosine deaminases acting on RNA. Inosine is read as a guanosine (G) by cellular enzymes, which has the potential to change protein-coding regions and protein-binding sites. The A-to-I modification may also change the secondary structure of noncoding regions. For some genes, like the glutamate receptor in mice, RNA editing is required to produce a functional protein (Wright & Vissel, 2012).

To determine the influence of DR on editing, we quantified A-to-I conversions occurring within each of four biological replicates for all test groups in our dataset. For an edit site to be included, we required a minimum editing frequency of 10%. Under AL, we detected an average of 125 putative editing sites in the total fraction, which was significantly decreased to an average of 70 in the translated fraction (Fig 4A), indicating that the occurrence of A-to-I editing is negatively associated with translation ($P = 0.029$, Wilcoxon rank sum test with continuity correction). DR amplified this difference, increasing putative editing sites to 154 with a concomitant decrease to 47 sites in the translated fraction ($P = 0.021$, Wilcoxon rank sum test with continuity correction). A similar pattern is observed with respect to the frequency of editing at these sites (Fig S3A). The overlap of editing sites among the different experimental groups is shown in Fig 4B, which shows 39 sites common to all samples, but none that are exclusive to the translated mRNA under DR. A list of the editing sites, their average editing frequencies with respect to the frequency of editing at these sites (Fig S3A). The overlap of editing sites among the different experimental groups is shown in Fig 4B, which shows 39 sites common to all samples, but none that are exclusive to the translated mRNA under DR. A list of the editing sites, their average editing frequencies among the different experimental groups, and the genes in which they occur in are provided in Table S7. The GO term enrichment for biological processes of genes with altered editing frequency is also provided in this table and includes functions pertaining to the proteasome, protein modification, and cell cycle. Together, these results suggest that A-to-I editing may be a method to effectively diminish expression of specific genes under DR.

The composition of 3’ UTRs can influence both transcript stability and translatability (Mayr & Bartel, 2009; Theil et al, 2018; Tushev et al, 2018). Considering all editing sites detected in the dataset, 65% occurred in the coding sequence (CDS), whereas 35% occurred in the 3’ UTR (Fig 4C). The average 3’ UTR length of coding genes quantified in this dataset was only 14.6% of average CDS length, indicating that RNA editing is enriched within this region. To address whether editing of 3’ UTRs influences translation rates, linear regression was performed for CDS-edited and 3’ UTR-edited genes.
with respect to translational regulation (Fig 4D). Genes with a higher frequency of editing in their 3’ UTRs under DR were more likely to be translationally suppressed \((r = -0.887, P = 1 \times 10^{-5})\). No significant correlation was observed for genes CDS-edited messages \((r = 0.195, P = 0.41)\). Thus, editing events localized to the 3’ UTR negatively correlate with translation under DR.

Among the genes with differential A-to-I editing in their 3’ UTRs was \(\text{eif2-alpha}\), a subunit of the eukaryotic translation initiation factor-2. This factor is required for delivering charged tRNAMet to the ribosome to initiate translation (Sokabe et al, 2012). Editing of the 3’ UTR of \(\text{eif2-alpha}\) was observed in a comparison of wild-type worms to \(\text{adr-1}\) adenosine deaminase mutants (Washburn et al, 2014). Two edits were present in the 3’ UTR of \(\text{eif2-alpha}\) with significantly different frequencies between total and translated RNA under DR (Fig S3B and C). In accordance with results for mean editing frequency in Fig S3A, the editing frequency at both sites was lower in the translated fraction under DR, suggesting that transcripts edited at these loci are translationally suppressed. The expression of the A-to-I editing regulator gene \(\text{adr-1}\) and the gene encoding its binding partner \(\text{adbp-1}\) was reduced in the translated fraction under DR (Fig S3D). Conversely, the expression of \(\text{adr-2}\) was slightly increased under DR. These expression changes in adenosine deaminases acting on RNA are a likely explanation of the changes in editing frequencies observed under DR. In line with the above observations, the robust translational promotion of \(\text{eif2-alpha}\) under AL conditions was partially attenuated under DR (DPAR of \(-0.295, \text{Fig S3E}\)), suggesting that edits in it’s 3’ UTR may be responsible for its translational attenuation. The edit occurring at position 2076705 occurs in a stem loop in the predicted secondary structure of the 3’ UTR of \(\text{eif2-alpha}\) (Fig S3F). As stem loops allow for specific recognition of RNA by binding proteins (Mattaj, 1993), this edit could control which regulatory factors bind to the 3’ UTR of \(\text{eif2-alpha}\). In addition, the edit at position 2076770 removed one of the seed match pairings of \(\text{mir-1820}\) and of \(\text{mir-792}\) (Fig S3F), which could change the translational regulation of \(\text{eif2-alpha}\).

Annotated RNA-binding sequence motifs are enriched among differentially translated mRNA under DR

RBPs and miRNAs can alter the propensity of a target transcript to be translated. Although they differ in their mode of action, both RBPs and miRNAs rely on sequence motifs to recognize mRNA targets. In addition to cis-regulatory elements within UTRs of mRNA and corresponding trans-acting factors, other characteristics including length and secondary structure can affect translatability (Ringnér & Krogh, 2005; Zid et al, 2009; Rogers et al, 2011). Therefore, we characterized the 3’ UTRs of promoted and suppressed DPAR genes in terms of length, GC content, free folding energy, and presence of RBP or miRNA motifs to determine their relevance in gene regulation under DR.

The average 3’ UTR length of promoted (148.2 bp) DPAR genes were significantly shorter than that of the quantified gene set (180.6
Table 1. Characterization of 3' UTRs of genes with promoted or repressed polysomal association under DR.

<table>
<thead>
<tr>
<th></th>
<th>Promoted</th>
<th>Repressed</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean BP</td>
<td>148.2</td>
<td>170.6</td>
<td>180.6</td>
</tr>
<tr>
<td>SD BP</td>
<td>124.2</td>
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<td>0.271</td>
</tr>
<tr>
<td>SD GC</td>
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<td>0.067</td>
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<tr>
<td>P-value GC</td>
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<td>0.205</td>
<td>n/a</td>
</tr>
<tr>
<td>Mean MFE</td>
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<td>-21.5</td>
</tr>
<tr>
<td>SD MFE</td>
<td>27.0</td>
<td>32.9</td>
<td>25.6</td>
</tr>
<tr>
<td>P-value MFE</td>
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<td>0.912</td>
<td>n/a</td>
</tr>
<tr>
<td>n</td>
<td>446</td>
<td>81</td>
<td>3675</td>
</tr>
</tbody>
</table>

Promoted, genes with positive DPAR; Repressed, genes with a negative DPAR; All, all quantifiable genes in the dataset; mean GC, the mean GC content of the UTR sequence; avg BP, the mean sequence base pair length; mean MFE, the mean minimum free energy in kcal/mol; n, the number of sequences available for use in the analysis.

Values in bold are significantly (Wilcoxon rank sum test, P-value < 0.05) different compared with all quantifiable genes.
were shown previously to be down-regulated under DR in *C. elegans* (Vora et al, 2013; Kogure et al, 2017). Deletion of mir-80 recapitulates many of the physiological and longevity benefits of DR (Vora et al, 2013). Furthermore, *mir-58* was recently shown to be partially required for life span extension in a genetic model of DR in *C. elegans* (Zhang et al, 2018). Based on our in silico analysis and the down-regulation of *mir-58* and *mir-80* under DR, they seem to play a role in longevity by regulating the translation of select transcripts.

**Intron retention increases under DR by bacterial dilution**

The alternative splicing (AS) of mRNA can produce gene isoforms that are differentially translated. AS can lead to transcripts with premature termination codons (PTCs), which are targeted for degradation by nonsense-mediated decay (NMD), an mRNA quality control surveillance mechanism that degrades aberrant mRNA. However, the full range of NMD targets extends beyond aberrant gene products, and some studies suggest that AS and NMD are coupled (AS-NMD) to enable regulation of specific genes via translation (Barberan-Soler et al, 2009; Ge & Porse, 2014). Exactly how NMD targets non-aberrant mRNA is unknown, but these and other studies point to the existence of an underappreciated form of gene regulation.

To assess AS-NMD in the current study, we focused on a type of AS in which an intron is retained in the mature mRNA, which usually leads to out-of-frame translation and one or more PTCs. An average of 1.5% of reads aligned to introns under AL, which was increased to 2.2% under DR (*P* = 0.002, two-way t test, Fig 7A). The change in intron retention under DR suggests either diminished NMD, increased AS, or both. Next, we quantified intron retention in the polysome-associated fraction. NMD takes place during a pioneering round of translation, so we expected mRNAs with retained introns to be depleted among polysomes. Indeed, intron retention was lower in...
the translated fraction than the total fraction under both AL (1.0%, \(P\)-value = 0.002) and DR (1.2%, \(P\)-value = 0.003). However, the presence of intronic reads in the polysomal fraction suggests that their associated transcripts escaped NMD. Furthermore, although more intron retention was detected in the translated fraction under DR than AL (two-way \(t\) test, \(P = 0.017\)), the ratio was smaller than that observed between total and translated under AL (\(P = 0.006\), two-way ANOVA). Thus, although there are more retained introns among both total and translated mRNA under DR, there is a decrease in the frequency with which intron-bearing mRNA makes it into the translated fraction. These results suggest that intron retention, like 3' UTR editing, is a method to inhibit protein synthesis of specific genes during adaptation to DR conditions.

Having established that there are dynamic changes in the global frequency of intron retention under DR, we sought to determine changes in the distribution of intron retention on a gene-by-gene basis. Using a fold-change threshold of 2 and a FDR cutoff of 0.05, 1,029 genes showed increased intron retention and 36 genes exhibited decreased intron retention under DR (Fig 7B). There was a significant overlap in genes with intron retention in the current study with those determined to have intron retention in an \(eat-2\) genetic model of DR in \(C.\) elegans, where increased retention of introns was also observed (Fig 7C; Fisher's exact test, \(P = 0.017\); Tabrez et al, 2017). In the translated fraction, 539 genes showed increased intron retention under DR, whereas 42 genes had decreased intron retention (Fig 7B). This suggests that changes in intron retention were because of an increase in the number of genes with retained introns. This also suggests that the increased frequency of introns under DR shown in Fig 7A was not simply because of increased frequency of introns within a set of genes common to both AL and DR conditions.

Comparison of genes with increased intron retention under DR in the total and translated fractions shows that most, but not all, of those in the translated pool are a minority subset of genes in the total fraction (Fig 7D). Interestingly, 97 genes exhibited a higher level of intron retention among translated mRNA than among total mRNA, suggesting that the retained introns promoted association with translation machinery in these instances (Fig 7D). Results indicated that intron retention was not always associated with exclusion from translation. This suggested that there was more than just nonsense associated with these transcripts, and we further investigated the connection between intron-bearing mRNAs and translation.

To identify dynamic changes in translation of intron-bearing genes between AL and DR, we used DPAR-type analysis similar to that carried out in Fig 2D. Seventy-four intron-retaining genes were associated more with polysomes under DR than AL and 139 were associated less (Fig 7E and Table S10). Those intron-bearing transcripts translationally promoted under DR were enriched for biological processes related to cell localization and signal transduction, whereas those translated less under DR were enriched for biological processes including cell cycle, stress response, and telomere maintenance (Fig 7F and Table S11). Enrichment of genes governing specific biological process suggests that NMD may be selective in a manner that regulates differential gene expression as opposed to just being a quality control process.

Although we expect the majority of gene products with retained introns to be nonfunctional because of frame shift and/or the
presence of PTCs, we sought to examine these assumptions empirically and inspect the structure of genes with retained introns. We examined some of the up-regulated genes more closely to confirm that intron retention was associated with inclusion of one or more PTCs. Table S10 shows the frequency of intron retention for individual genes. We first investigated the basic helix-loop-helix protein (bHLH) mdl-1 because of its role in regulating C. elegans life span (Nakamura et al, 2016) and because it was previously reported to undergo intron retention (Tabrez et al, 2017). The predicted CDS of the intron-bearing isoform of mdl-1 contained an out-of-frame PTC occurring after its annotated bHLH domain (Fig S4A). Therefore, although the retained intron isoform would encode for a truncated protein, it could still have a function through the expressed bHLH domain.

The gene F13G3.6 was investigated because it was reported to have a PTC-bearing isoform whose expression is dependent on the activity of the NMD gene smg-2 in C. elegans (Son et al, 2017). This gene is similar to human B3GNTL1, which plays a role in elongating N-glycans on mucin proteins. Exons upstream of the intron contained a glycosyl transferase family two domain. Interestingly, the retained intron results in a single PTC with no frame shift (Fig S4B). In such instances, it is possible that translational read-through of the PTC occurs to produce a full-length product (Oren et al, 2014). Finally, we examined the gene encoding selenoprotein trxr-1 as it mediates healthy longevity in response to treatment with the organic form of selenium (Chang et al, 2017) and only retained a portion of the annotated intron. The retention event resulted in a significant (twofold, FDR < 0.05) increase in expression under DR.

### Figure 7. Intron retention is increased under DR to drive changes in translation.

(A) The reads aligning to introns as a percent of total aligned. *P*-values from two-tailed t test, n = 4. (B) Number of genes with increased or decreased intron retention under DR in either the total or the translated fraction. (C) Venn diagram showing the overlap of genes with intron retention under DR by bacterial dilution in the current study and those identified in the eat-2 genetic model of DR. (D) Overlap of genes with increased intron retention under DR in either the total or the translated fraction. Only genes with >twofold change with FDR >0.05 were considered. (E) Retained intron transcripts translationally promoted or repressed significantly (>twofold, FDR < 0.05) under DR. Black circles represent genes with similar translation between diets, blue circles represent genes with twofold or greater DPAR. Red lines delineate the fold twofold change cutoff. Inset, 74 genes were translationally promoted and 139 were translationally repressed. (F, G) Biological GO terms enriched among retained intron genes with (F) promoted or (G) repressed translation under DR. *P* < 0.05, modified Fisher’s exact test. Functionally similar GO terms from identical groups of genes were manually removed. (H) Mutants defective in NMD genes smg-6 or smg-7 showed a reduction in life span under DR, in contrast to wild-type worms (*P* < 0.001, long-rank test). Representative life spans are shown; full dataset found in Table S10. TO, total fraction; TR, translated fraction.
addition of 6 base pairs (bp) to the 5' end of exon 5, which did not induce a PT or frame shift (Fig S4C). Therefore, while unlikely to be directly regulated by NMD, this isoform may represent a new, previously annotated isoform of trxr-1 that is better translated under DR.

NMD genes smg-6 and smg-7 are required for DR-mediated life span extension

In C. elegans, NMD is governed by the activity of several genes, including smg-1/2/3/4/5/6/7, which are responsible for the detection of aberrant transcripts, releasing the stalled ribosome, and degrading the transcript (Hug et al, 2016). The expression of several smg genes were altered in the DR mRNA-seq dataset (Fig S4D). Given that the translation of NMD-prone transcripts seemed to be regulated by DR and that NMD has been shown to play a role in ILS-mediated longevity (Son et al, 2017), we hypothesized that NMD plays a role in DR-induced longevity. We tested the importance of NMD in longevity using mutants defective in smg-1/2/3/4/5/6/7 subject to AL or DR starting at adulthood. Interestingly, the lines smg-6(r896) and smg-7(r1197) were shorter lived under DR than AL (P-value < 0.0001 for both; log-rank test), demonstrating their requirement for DR-induced longevity (Fig 7H). In comparison, the other smg mutants (smg-1/2/3/4/5) were longer lived under DR than AL, albeit this extension was attenuated compared with wild-type worms (Table S12). The requirement of smg-2 for the full effects of DR-induced longevity in the eat-2 mutant and by bacterial dilution was previously shown (Tabrez et al, 2017). The genes smg-6 and smg-7 are each thought to participate in NMD by degrading the transcript after it has been detected and the ribosome released. Although smg-6 is thought to degrade transcripts directly by its endonuclease activity, smg-7 is thought to degrade transcripts by recruiting deadenylation factors. Together, these observations raise the possibility that the selective degradation of NMD-prone transcripts by smg-6 and smg-7 can dictate which transcripts are translated under DR to influence longevity.

Discussion

Translation is expensive with respect to the energy and raw materials that it consumes. Low nutrient levels lead to low global translation. However, our understanding of how the stoichiometry of protein synthesis for specific individual gene products changes under DR through selective translation is limited. To elucidate this process, we sought to identify translationally regulated genes and potential mechanisms of posttranscriptional regulation that influence their translation. Using a combination of polysome profiling and mRNA sequencing, we generated diagnostics of the transcriptome and translome. In silico analysis was used to assess the relationship between these diagnostics and how this relationship is changed when nutrients are restricted. It also provided a means by which to probe differentially expressed genes for annotated cis-elements and corresponding trans-acting factors, generating a roadmap for future analyses testing mechanisms of posttranscriptional regulation that contribute to differential expression. The use of RNAi allowed us to determine which differentially expressed genes and cellular processes, like NMD, are important contributors to the increased life span associated with DR.

An important early step in trying to understand how somatic protection is conferred by a health-promoting intervention like DR is to understand how expressions of genes change to meet the requirements of adaptation. Three genes among the 100 showing the greatest transcript-level decrease in expression under DR increased life span when knocked down with RNAi under AL. fxb-24 and sdz-33 encode highly related F-box-containing proteins. The F-box motif was first observed as a constituent of Skp, Cullin, F-box (SCF) ubiquitin–ligase complexes and helped confer specificity to proteolytic substrates (Skowyra et al, 1997). Since then, many other genes encoding F-box motifs have been identified. The motif is structured with about 50 amino acids that function in protein–protein interactions, which are highly abundant in C. elegans (Kipreos & Pagano, 2000). The third gene was D1086.3, a gene of unknown function that was also the only one tested for life span that was also selectively down-regulated via translation.

Selective translation of stress responsive genes important for longevity has been previously described in C. elegans ILS mutants (McColl et al, 2010) and in a model of restricted nutrient-responsive translation (Rogers et al, 2011). In Drosophila melanogaster, selective translation enhanced synthesis of genes encoding mitochondrial components on a form of DR involving restriction of yeast extract (a primary source of protein; Zid et al, 2009). Inhibition of the nutrient-responsive TOR complex in mouse embryonic fibroblasts selectively suppressed ribosomal genes and promoted translation of several transcription factors, including Foxo7 (Thoreen et al, 2012). We observed translational suppression of ribosomal genes in the current study and other genes involved in translation (Fig 2G and Table S3). Two of these genes, iff-1 and pab-1, are translation initiation factors that increased life span when knocked down in fully fed wild-type animals.

In addition to direct regulators of translation, other repressed DPAR genes involved in life span regulation encode chaperones. The largest increase in median life span was observed for daf-21, the C. elegans ortholog of human HSP90. Although it has been previously reported to increase life span (Horiyaka et al, 2015; Sutphin et al, 2017), this is the first study to demonstrate its translational regulation in the context of DR. DAF-21/HSP90 serves to promote growth and reproduction by keeping growth-related kinases and transcription factors in a near-native conformation that facilitates their activation (Mitra et al, 2016). HSP90 also sequesters the HSF-1 heat shock transcription factor, inhibiting its ability to trimerize and up-regulate expression of heat shock protein genes (Zou et al, 1998). The translational down-regulation of daf-21 under DR makes sense given that there should be less need for activation of growth-related kinases and transcription factors in low-energy conditions when nutrients are depleted. The chaperonin gene, cct-4, was translationally down-regulated under DR and increased life span upon knockdown despite the fact that loss of cct-4 is associated with a reduction in skn-1 transcriptional activity (Kahn et al, 2008). skn-1 is the only worm ortholog of mammalian nuclear factor-erythroid-related factor (Nrf) transcription factors and functions in the p38 MAPK pathway to regulate the oxidative stress response. Its transcriptional activity is inhibited by ILS (Tuttle et al., 2009).
et al., 2008), and it is considered to be a longevity factor by promoting somatic maintenance. It is unclear why low cct-4 translation supports increased life span given its positive correlation with at least one skr-1 target, gst-4. It is possible that other skr-1 targets are not similarly affected by cct-4 expression.

Translationally down-regulated genes D1086.3 and kbp-1 were, for the first time, identified as life span regulators in our RNAi screen. Interestingly, we did not observe life span extension in our RNAi screen for certain repressed DPAR genes previously shown to regulate life span. For example, expression of shr-1 and ncbp-2 are positively associated with longevity, whereas expression of cyc-2.1 is negatively associated with longevity but had no effect when knocked down using RNAi in the present study. The importance of shr-1 for increased life span is specific to attenuated ILS in daf-2 mutant backgrounds of multiple alleles tested and does not regulate life span in an eat-2(ad1116) genetic model of DR (Ghazi et al., 2007). RNAi targeting the nuclear cap-binding protein gene ncbp-2 was only shown to shorten life span when initiated during development, which can also result in severe defects and lethality (Büssing et al., 2010). cyc-2.1 encodes a component of the electron transport chain, which only extends life span in N2 wild-type animals when it is knocked down during development. Thus, it is not surprising that these genes did not regulate life span in our longevity screen that began during adulthood.

A novel association between RNA editing and translation under DR

Although RNA editing frequencies were previously shown to be regulated by neuronal stimulation (Tariq et al., 2013), regeneration (Witman et al., 2013), and hypoxia (Ben-Zvi et al., 2013), this is the first study to reveal widespread changes in editing because of nutrient limitation. A-to-I RNA editing increased under DR, especially within the 3’ UTRs, and such editing was associated with translational suppression. Conversely, although editing events occurred in the CDS, they were less frequent and were not associated with translational suppression. Together, these results indicate that RNA editing events are dynamic and likely to play a role in the adaptive response to DR.

Although a link between editing of individual genes and longevity remains to be established, polymorphisms in mRNA editing genes have been associated with longevity in humans (Sebastiani et al., 2009). The same study also demonstrated that loss the orthologous editing genes in C. elegans were required for longevity (Sebastiani et al., 2009). This raises the possibility that mRNA editing regulates the selective translation of transcripts with inputs to longevity. A provocative example of this in the current dataset was the editing of the 3’ UTR of eif-2alpha. Furthermore, the enrichment of RNA editing sites within 3’ UTRs was shown to overlap frequently with miRNA binding sites (Gu et al., 2012). Thus, RNA editing may influence expression by introducing or removing miRNA binding sites.

RBP and translation regulation under DR

Our screening of RBP motifs implicated pab-1 in the regulation of translationally promoted genes under DR. This gene encodes for the cytoplasmic poly-A-binding protein, referred to as PABPC1 in mammals. It has several molecular functions associated with it, the most prominent of which is its ability to bind to poly-adenosine stretches in the 3’ UTR of mRNA and then to associate with factors in the 5’ UTR to promote translation initiation. PABPC1 also regulates the expression of specific mRNA by binding to regions outside of the polyA tail (Smith et al., 2014). This mRNA-specific regulation can be mediated by interactions with miRNA (Flamand et al., 2016), participation in NMD (Brook & Gray, 2012), or through association with the 3’ UTR instead of the polyA tail (Burgess & Gray, 2010). Thus, pab-1 may be important for multiple forms of differential translation under DR.

Translational preference for trans-spliced products is reversed for the subset of SL genes in operons during adaptation to DR

5’ UTRs of C. elegans transcripts are frequently trans-spliced, which is a feature not only common to nematodes but also to flatworms, protostomes, sponges, cnidarians, chaetognaths, crustaceans, rotifers, and tunicates (Pouchkina-Stantcheva & Tunnaciffe, 2005; Zayas et al., 2005; Hastings, 2005; Zhang et al., 2007; Marlétxaz et al., 2008). SL sequences in nematodes bear trimethylguanosine caps (m(2,3,5)G; Liou & Blumenthal, 1990), in contrast to native 5’ UTRs, which contain a monomethylguanosine (m(1)G) cap (Sonenberg, 2000). Under well-fed conditions, we found that trans-spliced mRNA was translated better than mRNA with the native 5’ UTR, supporting previous analysis (Yang et al., 2017). Although this pattern was maintained under DR, it was modestly but significantly attenuated for SL1 spliced genes (Fig 3B).

Interestingly, despite the preference for SL-containing mRNA to be translated under normal conditions, both SL1 and SL2 genes were underrepresented among promoted DPAR genes (Fig 3C and D). This was also true for polycistronic genes contained in operons, which represent a subpopulation of trans-spliced products that accounts for ~17% of all protein-coding genes in C. elegans (Blumenthal & Gleason, 2003). Unlike bacterial operons, nematode polycistrons are separated posttranscriptionally and translated separately. The first gene within an operon is spliced to SL1, and subsequent genes are spliced to SL2. Interestingly, nearly half of the DPAR genes down-regulated in the transition from AL to DR conditions reside in operons. Although it is not clear how they are down-regulated, co-regulation of multiple genes by a single promoter could represent an optimization of gene expression for growth and reproduction under favorable conditions. Unfavorable conditions may then necessitate differential expression of genes under the same promoter, which could be achieved through translational regulation. However, because of the differences in the broader trend for translational regulation of trans-spliced genes from the subset of those in operons, we surmise that the presence of SLs, alone, cannot account for the differential translation of operonic genes under DR.

DR increases intron retention products and differentially regulates NMD targets

We found evidence that DR increases the prevalence of intron retention and alters NMD. Furthermore, we found that certain NMD
genes that play a role in target specificity and degradation are required for the benefits of DR. How AS-NMD is integrated to influence differential gene expression remains to be fully elucidated. With respect to splicing, there is a limited but growing body of evidence pointing to changes in AS according to dietary and metabolic conditions. For example, DR is associated with changes in AS for individual metabolic genes in mammals (Gallardo et al., 2005; Fernández et al., 2009; Kaminska et al., 2014). Furthermore, hepatic transcripts in caloric restricted primates exhibited increased alternative exon use, including genes related to fatty acid metabolism (Rhoads et al., 2018). Conversely, obesity is associated with diminished expression of several splicing factors in liver and skeletal muscle in a manner that contributes to increased lipogenesis (Pihlajamäki et al., 2011). In a recent non-DR-related study of splicing in the tea plant Camellia sinensis, the predominant form of AS was intron retention, which occurred in genes related to the spliceosome and mRNA processing (Zhu et al., 2018). That regulators of splicing are, themselves, highly subject to alternative processing is conserved in animal studies. In mammals, AS is regulated by members of the SR protein family that alternatively splice a portion of their own transcripts (Lareau et al., 2007). These splice variants are normally targeted by NMD to limit total SR protein expression. Our analysis of intron retention suggested that coupling of AS-NMD is modulated under DR, in part, by changing the selectivity toward which transcripts are detected and degraded. Observations are in line with those obtained from cell culture exposed to rapamycin, a drug that inhibits the DR-related TOR pathway, in which the selectivity of NMD toward transcripts was also modulated (Martínez-Nunez et al., 2016). Taken together, studies point to an adaptive mechanism of DR that functions by controlling productive splicing and turnover.

The idea of regulated AS-NMD was previously invoked to explain differential expression during development in C. elegans (Barberan-Soler et al., 2009). Recently, Tabrez et al. (2017) used a genetic model of DR in C. elegans and identified more than 400 differential intron retention events. The authors suggested that AS under DR is needed to diversify the proteome in a way that is conducive for longevity and additionally requires NMD to fine-tune gene expression. The same eat-2 mutant was found to have increased splicing in the early, healthy part of life (Heintz et al., 2016). Thus, although it is clear that AS and intron retention is modulated by DR in a way that may affect longevity, the roles of AS-NMD on differential gene expression are, as yet, unclear.

This study was designed to characterize the posttranscriptional landscape of gene expression in response to DR and then survey the mechanisms that may govern this regulation. Our data provide evidence that DR invokes selective translation by acting through miRNA, RBPs, 3’ UTR length, RNA editing, and intron retention (Fig S5). One limitation to this approach was the use of whole worms as opposed to specific cell lines or tissues. Although the use of whole worms allows for the quantification systemic changes on translational regulation or effects occurring in large tissues like the intestine, tissue-specific effects, like RNA editing in the neurons, are likely lost by averaging the effect over all other tissues. The use of tagged RBPs, like poly-A-binding protein, expressed by tissue-specific promoters has been used in C. elegans to quantify tissue-specific gene expression in total mRNA pools (Blazie et al., 2015, 2017). Future studies may rely on similar technology to identify genome-wide tissue-specific patterns of differential processing and expression.

Materials and Methods

Nematode culture and polysome profiling

Caenorhabditis elegans strains were cultured at 20°C and maintained on normal growth medium (NGM) plates seeded with OP50. Developmentally synchronous animals from a 4-h egg lay were transferred to AL (1011 CFU/ml) or DR (1011 CFU/ml) reaching day 1 of adulthood. To inhibit bacterial growth, AL and DR plates contained 25 mg/ml carbenicillin. Because the DR conditions used in this study inhibit reproduction, 50 μg/ml FUDR was used to inhibit egg production equally under DR and AL. Polysome profiling was performed as previously described (Pan et al., 2007) after 4 d under these culture conditions. 100 μl of pelleted worms were homogenized on ice in 350 μl of solubilization buffer (300 mM NaCl, 50 mM Tris–HCl [pH 8.0], 10 mM MgCl2, 1 mM EDTA, 200 g heparin/ ml, 400 U RNAsin/ ml, 1.0 mM phenylmethylsulfonyl fluoride, 0.2 μg cycloheximide/ml, 1% Triton X-100, and 0.1% sodium deoxycholate). After homogenation, an additional 700 μl of solubilization buffer was added and the sample was incubated on ice for 30 min. Debris was pelleted by centrifugation at 20,000g for 15 min at 4°C. Of the resulting supernatant, 900 μl was applied to the top of a 10–50% sucrose gradient in high salt resolving buffer (140 mM NaCl, 25 mM Tris–HCl [pH 8.0], and 10 mM MgCl2) and centrifuged in a Beckman SW41Ti rotor at 38,000 rpm for 90 min at 4°C. Gradients were fractionated using a Teledyne density gradient fractionator with continuous monitoring of absorbance at 252 nm. RNA was extracted from polysome fractions and unfractionated samples using Trizol LS reagent according to the manufacturer’s protocol (Invitrogen Corp.). Eukaryote total RNA Nano chips were used in an Agilent Bioanalyzer for quality control of the resulting RNA.

Alignment of reads to the C. Elegans genome

Alignment of RNA-seq reads from each biological replicate to C. elegans genome version WS220 was performed using the splice junction mapper TopHat (ver 2.0.8.b) (Kim et al., 2013). TopHat was supplied with transcript annotations from ENSEMBL version 66 (Flicek et al., 2011), so that preference of aligning reads is given to the transcriptome (remaining reads are converted to genomic mappings and merged with the final output). Default settings of TopHat were used with the following exceptions: the mean mate inner distance was set to 200 bp, microexon search was enabled, and the library type was set to “fr-unstranded” to indicate that unstranded paired end reads were used.

Differential expression

Aligned reads were counted per gene using the python script HTseq (Anders et al., 2015). Differential expression and dataset normalization was performed using the Bioconductor package edgeR.
miRNA relative quantification

Samples were day 4 adult N2 worms subjected to AL food or DR by bacterial dilution starting at adulthood. Biological triplicates were performed for each treatment. Worms were washed off from NGM plates with 1 ml of M9 buffer and allowed to gravity settled. Settled worms were washed twice with M9 to remove bacterial contamination and flash frozen before storage at ~80°C. RNA extraction with Trizol Reagent (Life Technologies) was performed according to the manufacturer's instructions until phase separation. The aqueous phase was then used as starting sample for further purification using the RNA Clean & Concentrator-5 system (Cat. No. 1016; Zymo Research) following the manufacturer's protocol recommended for Trizol Clean-up. RNA quality was analyzed using the NanoDrop ND-1000 Spectrophotometer (software v3.8.1). miRNA-specific cDNA was prepared using the qScript microRNA cDNA Synthesis Kit (Cat. No. 95107-025; Quantabio) following the manufacturer's protocol using 316 ng. The C. elegans mature miRNA sequences were obtained from miRbase (http://www.mirbase.org/index.shtml). All the miRNA members of families predicted to be enriched among DPAR genes (Fig 6B) were included as were their 5′ (5p) or 3′ prime (3p) product partners. In addition, primers for both the 3p and 5p products of mir-2, mir-46, and mir-47 were included as potential normalizers as they were previously accessed in C. elegans to be stably expressed under stress (Kagias et al, 2014). qPCR reactions consisted of 1× rAmp qPCR Green Master Mix (Denville Scientific/Thomas Scientific, 5 μm forward primer, 5 μm PerfeCta Universal Primer, and 3.16 ng RNA equivalents of cDNA all in a 10-μl reaction volume. qPCR data were collected using the LightCycler 480 (SW 1.5; Roche) equipped with a 384-well block. Thermal cycling was as follows: one step hold at 95°C for 2 min, 40 cycles of 95°C for 5 s/60°C for 20 s (data collection at 60°C), and one step melt with continuous data collection for melting curve analysis. Cycle threshold values from qPCR were analyzed with a modified version of Global Pattern Recognition (GPR) (Akilesh, 2003), and threshold cutoff setting was set to 35. GPR generates aggregate P-values corresponding to the likelihood that the gene is changing between treatments based on all using other assays as normalizers.

Expression profile clustering

Genes with a significant twofold or greater difference in relative expression between total and polysome-associated mRNA under DR but not AL were clustered together. Before clustering, the expression of each gene among the four experimental groups in was centered around its mean expression in the dataset. Clustering was performed with the Partitioning around Medoids algorithm using the pam() function and evaluated using silhouette widths (Rousseeuw, 1987) with the silhouette() function, both contained in the R package “Cluster”. The maximal number of clusters to use was determined by iteratively running the Partitioning around Medoids algorithm while sequentially increasing the number of clusters. Based on the experiences of Kaufman & Rousseeuw (2005), a silhouette width cutoff of 0.25 was used as the lower limit for a cluster to have substantial structure. The highest cluster number among all iterations with all clusters having substantial structure was three.

RBP motif enrichment

Experimentally determined and homology inferred position weighted matrices for RNA-binding motifs of C. elegans proteins were downloaded from the CISBP-RNA database (Ray et al, 2013). Enrichment for each motif among genes translationally promoted or suppressed under DR was calculated using the R package “PWMenrich”. Background correction for nucleotide composition was applied with the function makePWMlogBackground() using 3′ UTRs from all quantifiable genes. 3′ UTRs were exported from the C. elegans genome version WS220; 3′ UTRs shorter than 12 bp were excluded from the analysis.

miRNA motif enrichment

Predicted targets of conserved miRNA families among nematodes were imported from http://www.targetscan.org/ release 6.2 (Jan et al, 2011). Only targets with a probability of conserved targeting (Pct) >0.8 were considered. Enrichment of miRNA binding sites among translationally promoted or suppressed genes compared with all quantifiable coding genes was calculated using Fisher’s exact test.

SLs

Annotations of the predominant SL present in C. elegans transcripts were taken from (Allen et al, 2011) Table S2. Unannotated genes were considered not to undergo trans-splicing and have their native 5′ UTRs. Comparison of translational regulation between AL and DR of genes with native, SL1, or SL2 5′ UTRs was performed using the Wilcoxon rank sum test with continuity correction.
Intron retention

Reads aligning to intronic or exonic sequences were counted for each biological replicate using HTseq (Anders et al., 2015) based on transcript annotations from ENSEMBL version 66. A minimum of four reads aligning to introns within a gene was required to include in the analysis. The amount of global intron retention was expressed as the percent of reads aligning to introns over all aligned reads. Significant differences in global intron retention were determined using t test. To calculate intron retention occurring between diets in the total or translated fraction for individual genes, the Wilcoxon rank sum test was used. To detect genes with intron retention differing between RNA fractions in a way dependent on DR, a linear model was used to determine significant interaction effects of diet and RNA fraction on intron retention. This was achieved using the lm() function in R to model the interaction effect of diet and RNA fraction on intron retention for each gene. Multiple testing was corrected for using the Benjamini–Hochberg method.

GO term enrichment

Enrichment of biological terms among gene lists was performed using DAVID (version 6.7) (Huang et al., 2008, 2009). The category GO_TERM_BP_FAT was used for annotations, and the list of quantifiable coding genes in our dataset was used as the background. For visualization, similar enriched GO terms based on the same subset of genes were manually removed to reduce redundancy; supplemental tables contain the full results. Genes lists submitted to DAVID analysis often had low conversion rates (<80%); therefore, it is likely that enriched terms will change as annotations become more complete.

Statistical analysis

Spearman correlations between gene abundance in the total and translated fractions was performed using the corr() function in the R package “Hmisc”. The distribution of fold change in gene abundance between the total and translated fractions was compared between AL and DR conditions using a two-sample Kolmogorov–Smirnov test.

Life spans and worm strains

All worm cultures were maintained at 20°C. Worms were subjected to RNAi treatments starting at day 1 of adulthood to avoid potential effects on development. To prevent contamination by progeny, FuDR was used at a concentration of 0.5 mg/ml in the plate. Worms were scored every other day for survival. Worms were scored as alive if movement was evident after gentle prodding of tail and head with a platinum worm pick. Worms with vulvar bursts or that had crawled off media were censored. Survival was plotted as Kaplan–Meier survival curves in GraphPad Prism (version 5) and analyzed by log-rank test using the “survival” package (version 2.44-1.1) in R. Three biological replicates were performed for each life span. The following strains were used in this study: N2, TR1331, CB4043, CB4354, CB4355, TR1335, TR1336, and TR2230.

RNA interference by feeding and DR

RNAi bacteria strains were cultured as previously described (Kamath et al., 2001). Worms were fed RNAi strains starting at day 1 of adulthood. Bacteria expressing dsRNA included: empty vector L4440 (Addgene), those from the Ahirnger library or if not available, from the Vidal ORF library (Source BioScience). For life spans involving both RNAi and DR, the worms were first exposed to regular concentrations of RNAi bacteria for 2 d before transferring to pepitone-free nematode growth media plates containing OP50 at the appropriate concentrations for AL (10^{11} CFU/ml) or DR (10^{11} CFU/ml). For the polysome profiling, worms were grown to maturity on OP50 until transferring to AL or DR plates as above.

RNA editing sites

To search for potential adenosine to inosine RNA editing sites, mRNA-seq reads from each biological replicate were compared with the reference genome WS220 for the presence of A to G SNPs using REDItools (Picardi & Pesole, 2013). The last three bases from each were trimmed, and only uniquely mapped reads from properly paired reads were considered. In addition, for each biological replicate, a minimum of five reads supporting the variation and an editing frequency greater than 10% was required. Significant differences in editing frequencies between experimental groups were determined using the Wilcoxon signed rank test.

GSEA

Comparison of differentially expressed transcripts in the total fraction of our dataset with those detected in a microarray experiment published by Honjoh et al (2009) was performed using GSEA version 2.0.9 (Subramanian et al., 2005). The processed data from the manuscript were downloaded from Array Express under the genome accession number GSE9682. The processed data were reformatted for GSEA, and Affy IDs were replaced with the gene ID for their matching transcript using Ensembl’s Biomart function. Of the 22,626 Affy IDs, 21,459 had a gene name assigned to them; those Affy IDs without a corresponding gene ID were not included in the analysis. The GSEA was run with 10,000 permutations based on shuffling the gene set, using the “weighted” enrichment statistic and “signal to noise” metric for ranking genes.

5’ and 3’ UTR characterization

5’ and 3’ UTRs were characterized separately based on length, GC content, and minimum free folding energy. Three groups of genes were considered: genes translationally promoted, genes translationally suppressed, and all quantifiable genes. Gene sequences from the 5’ or 3’ ends were exported from ENSEMBL version 66 using the getSequence() function in the biomart R package. As genes often encode for multiple isoforms, 3’ and 5’ UTR sequences from the predominately expressed isoforms across the experiment was used for analysis. Quantification of isoform expression was performed using cuffdiff with default parameters (version 2.1.1), and the predominantly expressed isoform was defined as the one with the highest average FPKM in the dataset. Fractional GC content and...
sequence length were calculated using the alphabetFrequency() function from the biostrings package. The minimum free folding energy was calculated using the RNAfold function of the Vienna RNA package (version 2.4.8) with default settings. The characterized values for translationally promoted and suppressed genes were compared with all quantifiable genes using the Wilcoxon rank sum test.

Data Availability

The raw and processed high-throughput sequence data from this publication have been deposited to the Gene Expression Omnibus database https://www.ncbi.nlm.nih.gov/geo/ under accession GSE119485.

Supplementary Information

Supplementary Information is available at https://doi.org/10.26508/lsa.201800281.

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Author Contributions

JA Rollins: data curation, formal analysis, methodology, writing—original draft, writing—review and editing.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

References


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