AT A GLANCE

RNA metabolism in neurodegenerative disease
Elaine Y. Liu, Christopher P. Cali and Edward B. Lee*

ABSTRACT
Aging-related neurodegenerative diseases are progressive and fatal neurological diseases that are characterized by irreversible neuron loss and gliosis. With a growing population of aging individuals, there is a pressing need to better understand the basic biology underlying these diseases. Although diverse disease mechanisms have been implicated in neurodegeneration, a common theme of altered RNA processing has emerged as a unifying contributing factor to neurodegenerative disease. RNA processing includes a series of distinct processes, including RNA splicing, transport and stability, as well as the biogenesis of non-coding RNAs. Here, we highlight how some of these mechanisms are altered in neurodegenerative disease, including the mislocalization of RNA-binding proteins and their sequestration induced by microsatellite repeats, microRNA biogenesis alterations and defective tRNA biogenesis, as well as changes to long-intergenic non-coding RNAs. We also highlight potential therapeutic interventions for each of these mechanisms.

KEY WORDS: Disease, RNA binding proteins, Microsatellite repeats, miRNA, tRNA, lncRNA, RNA

Introduction
Aging-related neurodegenerative diseases, such as Alzheimer’s disease (AD), Parkinson’s disease (PD), frontotemporal degeneration (FTD) and amyotrophic lateral sclerosis (ALS), among others, are relentlessly progressive and uniformly fatal neurological diseases that are characterized by irreversible neuron loss and gliosis. Although dementia prevalence as a percentage of the elderly has declined in developed countries, the absolute
number of dementia cases is growing as a result of an increase in the aging population (Langa et al., 2017). Thus, it is important for us to better understand the basic biological mechanisms that contribute to neurodegeneration.

Although much emphasis has been placed on the role of protein aggregates in neurodegenerative diseases, multiple lines of evidence also converge on altered RNA processing as a contributing factor in the pathogenesis of these diseases (Anderson and Ivanov, 2014; Belzii et al., 2013; Bentmann et al., 2013; Halliday et al., 2012; Ling et al., 2013). Defects at all levels of gene regulation, from RNA synthesis, processing, function and degradation, are associated with disease-specific alterations in RNA-binding proteins (RBPs), and in non-coding RNAs, such as microRNAs (miRNA), transfer RNAs (tRNA) and long-noncoding RNAs (lncRNA). Given that these basic processes are essential for normal and properly regulated gene expression, it is increasingly clear that aberrations in these processes can contribute to disease. In this Review and accompanying poster, we highlight several key themes that explain how different classes of RNAs or RBPs can impair gene regulation. We also highlight specific examples with evidence to show that improper RNA metabolism is a critical feature of neurodegeneration.

**RNA-binding proteins regulate RNA metabolism**

RBPs are essentially required at all levels of RNA processing in both the nucleus and cytoplasm where transcription, splicing, RNA stabilization, and RNA degradation occur (see poster panel A). Two notable examples of RBP defects occur in familial and sporadic cases of ALS and FTD. ALS is a neurodegenerative disease that leads to the loss of upper and lower motor neurons from the motor cortex and spinal cord, respectively, whereas FTD is associated with neuronal loss in the temporal and frontal cortex. Despite different areas of neuronal atrophy, a common link between ALS and FTD patients is a nuclear RBP called TAR DNA-binding protein-43 (TDP-43). Post-mortem brains from human ALS and FTD patients show a characteristic mislocalization of TDP-43 from the nucleus into phosphorylated, ubiquitylated cytoplasmic TDP-43 aggregates (see poster panel A) (Neumann et al., 2006). Indeed, rare disease-causing mutations in TARDBP, the gene encoding TDP-43, suggest that TDP-43 dysfunction is sufficient to cause ALS (Van Deerlin et al., 2008; Gitcho et al., 2008; Kahashi et al., 2008; Sreedharan et al., 2008), although the mechanism by which these mutations cause disease is unclear. TDP-43 functions ubiquitously in RNA processing, including splicing (Buratti et al., 2001; Ling et al., 2015; Shiga et al., 2012; Tollervey et al., 2011), stability (Costessi et al., 2014; Liu et al., 2012; Strong et al., 2007) and transport (Alami et al., 2014). Shortly after the discovery of TARDBP mutations, mutations in FUS, which encodes the nuclear protein fused in sarcoma (FUS) (also known as translated in liposarcoma, TLS), were identified in a subset of individuals with ALS, and FUS was revealed to be mislocalized to the cytoplasm (Kwiatkowski et al., 2009; Vance et al., 2009). Similar to TDP-43, FUS interacts with serine arginine (SR) proteins involved in RNA splicing (Yang et al. 1998) and regulates transcription by recruiting RBPs through non-coding RNAs (Wang et al., 2008). An additional example of abnormally localized nuclear RBPs is evident in individuals with multisystem proteinopathy (MSP), in whom mutations in the gene encoding heterogeneous nuclearriboprotein particle A1 (HNRP41) and A2B1 (HNRP4A2B1) contribute to disease. MSP is characterized by the progressive degeneration of muscle, brain, motor neurons and bone, which sometimes manifests as ALS or FTLD (Kim et al., 2013). Mutations in the gene encoding valosin-containing protein (VCP), a triple ATPase protein involved in many cellular functions including endolysosomal degradation, autophagy, and the ubiquitin proteasome system, also causes MSP (Watts et al., 2004). It is thought that the loss of RBPs through their nuclear mislocalization and/or the toxicity caused by their cytoplasmic aggregation can lead to disease, but their relative contributions to disease remain unclear. Mouse models with antisense oligonucleotides (ASOs) against Tardbp depleted TDP-43, show altered global RNA expression affecting 601 genes, and specifically neuronal genes with long introns (Polymeridou et al., 2011). To better understand the targets of these RBPs, TDP-43 and FUS have been immunoprecipitated from mice brains and rat primary neuronal cultures, revealing that these proteins bind to non-coding RNA sites, namely introns and 3′ untranslated regions (UTRs) of thousands of genes (Lagier-Tourenne et al., 2012; Sephton et al., 2011). Some of these genes include ncRNAs, like metastasis-associated lung adenocarcinoma transcript 1 (Malat1) and nuclear paraspeckle assembly transcript 1 (Neat1) (Lagier-Tourenne et al., 2012; Polymeridou et al., 2011; Tollervey et al., 2011). Thus, it is possible that the loss of RBPs influences the processing of these non-coding RNAs and contributes to global RNA dysregulation (see poster panel A). Given that the depletion of these RBPs alters the expression of thousands of genes, it is likely that some, or even all of these changes contribute to disease pathogenesis.

The formation of cytoplasmic RNA granules that lead to cytoplasmic aggregates has also been proposed to be pathogenic. When cells are stressed, cytoplasmic RNA granules that contain stalled translational complexes are formed. TDP-43, FUS, and other RBPs, such as hnRNPA1 and A2B1, localize to stress granules (Kim et al., 2013; Li et al., 2013). Indeed, RBPs with low complexity domains (LCD), such as TDP-43, FUS and hnRNPA1, can phase separate to create dynamic membrane-less organelles or liquid droplets that underlie the transient nature of stress granules (Coureyhaine et al., 2016; Molliex et al., 2015). The liquid properties of these organelles are dependent on their constituents. Namely, the intrinsic properties, type, concentration of the RBP, RNAs that the RBPs are bound to and the concentration of the RNA greatly influence these RNA granules (Kroschwald et al., 2015; Smith et al., 2016). For example, increasing the concentration of RBPs can reduce the liquid-like properties of these RNA granules, thereby promoting the formation of hydrogels and eventually an insoluble amyloid-like aggregate (Guo and Shorter, 2015; Kato et al., 2012; Lin et al., 2015; Molliex et al., 2015; Xiang et al., 2015). Indeed, disease-associated mutations within the LCDs of RBPs can enhance prion-like properties, and accelerate the shift from liquid to solid and disrupt ribonucleoprotein (RNP) granule formation (Murakami et al., 2015). At present, there is little evidence supporting amyloid-like fibrillar aggregates within neurons in ALS/FTD, but the relationship between other biophysical assemblies such as hydrogels, and neuronal aggregates is being investigated (Murakami et al., 2015). Thus, the formation of liquid droplets is another mechanism by which RBP disruption could contribute to disease (see poster).

The formation of cytoplasmic aggregates has also been implicated in neurodegenerative disease. Several different rat and mouse models, in which wild-type or mutant TARDBP or mutant FUS bearing ALS-associated mutations are overexpressed, develop cytoplasmic aggregation and exhibit features of ALS and FTD, including cortical and hippocampal neuronal loss and motor deficits (Huang et al., 2011; Igaz et al., 2011; Seekic-Zahirovic et al., 2016; Sharma et al., 2016; Tsai et al., 2010; Wils et al., 2010; Xu et al., 2010). However, none of these models has recapitulated the loss of endogenous nuclear TDP-43 or FUS. Despite the discrepancies
been identified to date (Loureiro et al., 2016). Some that form long expansions within gene bodies or in untranslated neurodegenerative diseases caused by repetitive DNA elements. Microsatellite repeat expansion disorders are a class of RBP sequestration by microsatellite repeat expansions between animal models and human pathology, there is

AT A GLANCE


shock response; (2) using heat shock protein (Hsp)104 achieved in several ways, for example by: (1) activating the heat shock response; (2) using heat shock protein (Hsp)104 ‘disaggregases’; or (3) by modulating the ubiquitin proteasome system and autophagy. HSPs function as molecular chaperones and are involved in protein folding, protein trafficking and in coping with denatured proteins (Lindquist and Craig, 1988). Prior work has shown that the overexpression of an HSP, heat shock factor 1 (HSF1), in rat primary neuronal cultures overexpressing wild-type TDP-43 prevents cytoplasmic aggregation of TDP-43 by interacting with other HSPs to enhance refolding. This reduces toxicity in a human bone marrow neuroblast cell line (SH-SY5Y) overexpressing either wild-type or mutant TDP-43 (Chen et al., 2016). Components of the heat shock response have also been engineered to remove aggregated proteins. Modified Hsp104 improves its disaggregation capabilities relative to the wild-type Hsp104, and is able to suppress FUS and TDP-43 toxicity in yeast. This provides a potential intervention to eliminate protein aggregates that contribute to toxicity (Jackrel et al., 2014). Enhancing components of the ubiquitin proteasome system or autophagy can also reduce these aggregates. For example, increasing cAMP levels with forskolin in human embryonic kidney cells (293A) enhances the ubiquitin proteasome system to clear aggregation-prone proteins, such as FUS and TDP-43, in cells overexpressing either wild-type or mutant forms of both proteins (Lokireddy et al., 2015). Furthermore, two different studies show that using autophagy activators rescues motor dysfunction in transgenic FTD mice and also improves survival of neurons and astrocytes derived from human induced pluripotent stem cells from ALS patients with a TARDBP mutation (Barmada et al., 2014; Wang et al., 2012b). Until the toxic mechanism that underlies RBP pathology is uncovered, it is difficult to determine which therapeutic intervention will be the most beneficial to patients.

RBP sequestration by microsatellite repeat expansions

Microsatellite repeat expansion disorders are a class of neurodegenerative diseases caused by repetitive DNA elements that form long expansions within gene bodies or in untranslated regions. Over 25 human genes that contain repeat expansions have been identified to date (Loureiro et al., 2016). Some neurodegenerative diseases caused by microsatellite repeat expansion have been linked to the sequestration of RBPs by expanded repeat sequences; these expanded sequences sequester RBPs away from their target RNAs, thereby altering RNA splicing and metabolism (see poster panel B) (Iwahashi et al., 2006; Jiang et al., 2004; Lee et al., 2013).

One example of altered RNA metabolism in neurological disease comes from the expansion of a CUG triplet in the 3' UTR of the gene DMPK, which leads to myotonic dystrophy (DM) (Brook et al., 1992). This expansion is transcribed into repeat RNA that forms aggregates, called RNA foci. These aggregates form within the nuclei of human-derived DM cells (Davis et al., 1997; Taneja et al., 1995) and recruit a class of RBPs that regulate alternative splicing, called the muscleblind-like proteins (MBNLs) (Miller et al., 2000). By sequestering MBNLs into RNA foci, mutant DMPK renders MBNLs unable to regulate splicing and the polyadenylation of hundreds of target genes (Batra et al., 2014; Goodwin et al., 2015; Wang et al., 2012a).

Similarly, repeat expansions associated with ALS/FTD and with Fragile X-associated tremor/ataxia syndrome (FXTAS) also sequester RBPs. In FXTAS, a short repeat expansion (<200 repeats) in the untranslated region of the gene FMR1 is transcribed into RNA and interacts with hnRNPs, MBNL1 and other RBPs (Iwajjasjo et al., 2006; Jin et al., 2007; Sofola et al., 2007), thereby altering splicing and microRNA biogenesis in affected individuals (Sellier et al., 2010, 2013).

In the most common inherited form of ALS/FTD, a hexanucleotide (G4C2) expansion in the first intron of the gene C9orf72 is bidirectionally transcribed into mutant RNA that forms aggregates in the nucleus (DeJesus-Hernandez et al., 2011; Gendron et al., 2013; Renton et al., 2011; Zu et al., 2013). Current evidence shows that RBPs involved in splicing, such as hnRNPs and the SR splicing factors that comprise the spliceosome, are sequestered by mutant repeat-containing RNA (Cooper-Knock et al., 2014; Lee et al., 2013) (see poster panel B). Additionally, the repeat expansion, which normally regulates vesicle trafficking and autophagy (Yang et al 2016; Aoki et al 2017), can interfere with transcription of the C9orf72 gene, resulting in haploinsufficiency of the protein product (Burberry et al., 2016; Ciura et al., 2013; DeJesus-Hernandez et al., 2011). Reduced transcription is due, in part, to hypermethylation of the mutant C9orf72 promoter. Hypermethylation is observed in about one third of C9orf72 mutation carriers and is associated with reduced mutant RNA accumulation and an attenuated clinical phenotype, suggesting that reduced transcription of mutant C9orf72 is actually protective against disease (Liu et al., 2014; McMillan et al., 2015; Russ et al., 2015). Thus, altered RNA metabolism is clearly implicated in neurodegenerative diseases caused by repeat expansions.

Given that repeat expansions cause widespread disruption to RNA metabolism, it will be challenging to target downstream processes for therapeutic intervention. Therefore, the most promising therapeutic approaches are those that work upstream to reduce the amount of repeat-containing transcripts. Several studies have used ASOs to target C9orf72 and DM expansions for degradation via an RNAse H-mediated pathway (Donnelly et al., 2013; Jiang et al., 2016; Lagier-Tourenne et al., 2013; Sareen et al., 2013; Wheeler et al., 2012). In fact, ASOs are already in clinical trial for the treatment of Huntington’s disease (HD) (Kordasiewicz et al., 2012) and have been approved for the treatment of spinal muscular atrophy (SMA) (FDA, 2016, http://www.fda.gov/NewsEvents/Newsroom/PressAnnouncements/ucm534611.htm). An alternative to targeting the repeat-containing transcript for degradation is to target proteins that are responsible for transcribing the repeat expansion. For instance, knockdown of the transcription elongation factor SUPT4H1 selectively decreases the repeat-containing RNA
in C9orf72 expansion fibroblasts derived from human carriers (Kramer et al., 2016). This strategy is attractive because transcription of the repeat is blocked in both the sense and antisense directions (Jiang and Cleveland, 2016; Kramer et al., 2016). A final therapeutic approach involves small molecules that target the expanded RNA to prevent their interactions with RBPs. Several of these compounds have been identified but are still in the early stages of development (Disney et al., 2012; Luu et al., 2016; Su et al., 2014). Although the repeat-expansion disorders offer a clear therapeutic target, reversing alterations in RNA metabolism will be challenging in neurodegenerative diseases that lack a clear genetic etiology.

**MicroRNA dysregulation in neurodegeneration**

Genes can also be regulated post-translationally via miRNAs, a class of small non-coding RNAs (18-25 nucleotides). miRNAs are initially transcribed by RNA polymerase II and then undergo sequential cleavage, first by Drosha and DGCR8 in the nucleus – to generate pre-miRNAs from pri-miRNAs – and then by Dicer after being exported into the cytoplasm, to generate a miRNA duplex (Lee et al., 2003). The miRNA duplex is unwound and one of the strands is incorporated into the RNA-induced silencing complex (RISC), where it binds to Argonaute (Agos) proteins (Schwarz et al., 2003). Agos then cleave the miRNA complementary to the miRNA or inhibit cap-dependent miRNA translation, both of which lead to translational repression (Chendrimada et al., 2005; Kiriakidou et al., 2007).

There are two ways in which miRNA dysregulation contributes to neurodegeneration: alterations to miRNA biogenesis or to miRNA expression, both of which can affect disease-associated genes. A notable example of altered miRNA processing is evident in ALS/FTD through TDP-43 function. In normal neurons, TDP-43 binds to Drosha in the nucleus to cleave select pri-miRNAs and to Dicer in the cytoplasm to cleave some pre-miRNAs (Ling et al., 2010). Agos then cleave the miRNA complementary to the miRNA or inhibit cap-dependent miRNA translation, both of which lead to translational repression (Chendrimada et al., 2005; Kiriakidou et al., 2007).

With the discovery that other classes of non-coding (nc)RNAs are essential for translation; they use aminoacyl-tRNA synthetase to specify an appropriate amino acid to a growing polypeptide chain during protein synthesis. tRNA biogenesis entails the transcription and processing of extracellular amyloid-β (Aβ) plaques and of intracellular phosphorylated neurofibrillary tangles composed of tau (Hardy and Selkoe, 2002). Beta-site APP-cleaving enzyme 1 (BACE1) and γ-secretase cleave amyloid precursor protein (APP), resulting in Aβ peptides that accumulate into plaques (Vassar et al., 1999). Multiple miRNAs have been implicated in Aβ production via BACE1 modulation and in tau phosphorylation that leads to hyperphosphorylated neurofibrillary tangle formation. Additionally, multiple miRNAs have also been implicated in ALS pathogenesis or as biomarkers of disease. For example, miR-23a is overexpressed in skeletal muscle biopsies from ALS patients. This miR-23a has been shown to regulate pexisome proliferator-activated receptor γ coactivator-1α, a regulator of mitochondrial biogenesis and function (Russell et al., 2013), which is important for skeletal muscle function. Using spinal cord from individuals with ALS, miR-155-5p and miR-142-5p are upregulated whereas let-7e, miR-148-5p, miR-133b, miR-140-3p and miR-577 are downregulated. These miRNAs regulate neuronal homeostasis, pathogenesis of ALS and other neurodegeneration-related transcripts ranging from ubiquilin, RNA-binding protein fox-1 and reelin among others (Figueroa-Romero et al., 2016) (see Table 1). Indeed, miRNA dysregulation can affect a range of disease-associated targets, which can contribute to neurodegeneration.

Altered miRNA signatures can also indicate potential diagnostic biomarkers. Indeed, various miRNA studies have identified differentially expressed miRNAs in post-mortem tissue or blood and in cerebrospinal fluid (CSF) that differ by disease stage (see Table 1) (Coggswell et al., 2008; Lau et al., 2013; Wang et al., 2011). Furthermore, miRNA-based therapeutics, such as miRNA mimics or miRNA antagonists (antagomirs), have been designed to either reverse the downregulation or upregulation of disease-associated miRNAs, respectively. These have been investigated for the treatment of cancer and cardiovascular disease (Broderick and Zamore, 2011; Thum, 2012; Wu et al., 2007b) but few have been used to treat neurodegeneration. One example of an antagomir in neurodegeneration comes from an AD mouse model (Tg2576) characterized by elevated levels of Aβ and the presence of amyloid plaques. The treatment of Tg2576 with an antagomir against miR-206, which targets brain-derived neurotrophic factor (Bdnf), increases Bdnf levels and improves memory function (Lee et al., 2012). Another example is based on the finding that miR-155 is increased in spinal cord from ALS patients and in an ALS mouse model with a mutation in SOD1. A locked nucleic acid (modified RNA nucleotide) anti-miR-155 reduces miR-155 levels in this mouse (Butovsky et al., 2015; Figueroa-Romero et al., 2016), thereby increasing survival and restoring the abnormal microglia and monocyte inflammatory signature (Butovsky et al., 2015). Because of the burgeoning importance of miRNAs in disease, it seems important to first investigate and develop an miRNA signature that is validated as a biomarker of disease by independent studies. Then, therapeutic interventions can be designed to target these specific miRNAs.

**Other non-coding RNAs in neurodegeneration**

With the discovery that other classes of non-coding (nc)RNAs are important for gene expression (Cech and Steitz, 2014), it is perhaps unsurprising that alterations to some of these other ncRNAs, such as to tRNAs and IncRNAs, can also lead to neurodegeneration. tRNAs are essential for translation; they use aminoacyl-tRNA synthetase to attach amino acids to the tRNA molecule, which then transfer the appropriate amino acid to a growing polypeptide chain during protein synthesis. tRNA biogenesis entails the transcription and...
splicing of tRNAs by complexes that involve the proteins CLP1 (cleavage and polyadenylation factor I subunit 1) and TSEN (the tRNA-splicing endonuclease complex) (Paushkin et al., 2004; Antonellis et al., 2003; Nangle et al., 2007; Xie et al., 2007). It is unclear why abnormalities in tRNA biogenesis result in different neurodegeneration-related transcripts. One mechanism proposed is the effect whereby mutant protein interferes with the wild-type protein activity; and (3) impaired axonal transport due to tRNA synthetase peripheral neuropathies but various mechanisms have been proposed, including: (1) loss of function of tRNA loading and subsequent protein translation inhibition; (2) a dominant-negative effect whereby mutant protein interferes with the wild-type protein activity; and (3) impaired axonal transport due to tRNA synthetase mutations, among others (Motley et al., 2010; Niehues et al., 2015).

### Table 1. MicroRNAs implicated in neurodegenerative disease

<table>
<thead>
<tr>
<th>Disease</th>
<th>MicroRNA</th>
<th>Regulation in human brain</th>
<th>Mechanism</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alzheimer’s disease</td>
<td>miR-107</td>
<td>Downregulated in AD cortex in stage-dependent manner</td>
<td>Increased BACE1 expression</td>
<td>Nelson and Wang, 2010; Wang et al., 2008</td>
</tr>
<tr>
<td></td>
<td>miR-29a/b-1</td>
<td>Downregulated in AD cortex</td>
<td>Increased BACE1/β-secretase expression</td>
<td>Hébert et al., 2008; Shiota et al., 2010</td>
</tr>
<tr>
<td></td>
<td>miR-146a</td>
<td>Upregulated in AD neocortex and hippocampus</td>
<td>Represses inflammatory response via downregulation of CFH, IRAK1</td>
<td>Cui et al., 2010; Iyer et al., 2012; Lukiw and Alexandrov, 2012</td>
</tr>
<tr>
<td></td>
<td>let-7</td>
<td>Upregulated in CSF of AD patients</td>
<td>TLR7 activation; causes neurodegeneration</td>
<td>Lehmann et al., 2012</td>
</tr>
<tr>
<td></td>
<td>miR-181c</td>
<td>Downregulated in CSF of AD patients</td>
<td>Regulates SIRT1</td>
<td>Cogswell et al., 2008; Schonrock et al., 2012</td>
</tr>
<tr>
<td></td>
<td>miR-34c</td>
<td>Upregulated in AD hippocampi</td>
<td>Regulates cognitive decline and reduced memory function</td>
<td>Zovolilis et al., 2011</td>
</tr>
<tr>
<td></td>
<td>miR-206</td>
<td>Upregulated in AD temporal cortex</td>
<td>Reduction of DBCF</td>
<td>Lee et al., 2012</td>
</tr>
<tr>
<td>Parkinson’s disease</td>
<td>miR-34b/c</td>
<td>Downregulated in affected brain regions</td>
<td>Reduction in cell viability by altering mitochondrial function, promotes oxidative stress and total ATP content</td>
<td>Miriones-Moyano et al., 2011</td>
</tr>
<tr>
<td></td>
<td>miR-126</td>
<td>Uregulated in dopaminergic neurons</td>
<td>Reduction of IGF1/PI3K/AKT signaling</td>
<td>Kim et al., 2014</td>
</tr>
<tr>
<td></td>
<td>miR-133b</td>
<td>Upregulated in midbrain of PD patients</td>
<td>Downregulation of PITX3 by suppressing dopaminergic neuron maturation and function</td>
<td>Kim et al., 2007</td>
</tr>
<tr>
<td>ALS/FTD</td>
<td>miR-132/212</td>
<td>Downregulated in frontal cortex of FTLD-TDP patients</td>
<td>Increases TMEM106B expression resulting in endolysosomal dysfunction</td>
<td>Chen-Potkin et al., 2012</td>
</tr>
<tr>
<td></td>
<td>miR-206</td>
<td>Upregulated in serum samples</td>
<td>Preferentially affects fast-twitch muscles of neuromuscular connections</td>
<td>Toivonen et al., 2014</td>
</tr>
<tr>
<td></td>
<td>miR-155-5p</td>
<td>Upregulated in spinal cord of fALS and sALS patients</td>
<td>Impairs microglia, phagocytic function in ALS mouse model</td>
<td>Butovsky et al., 2015; Figueroa-Romero et al., 2016</td>
</tr>
<tr>
<td></td>
<td>miR-23a</td>
<td>Upregulated in skeletal muscle biopsies from ALS patients</td>
<td>Regulates PPRC1e</td>
<td>Russell et al., 2013</td>
</tr>
<tr>
<td></td>
<td>miR-338-3p</td>
<td>Upregulated in blood leukocytes, CSF, serum, and spinal cord of sALS patients</td>
<td>Predicted to affect apoptosis and/or glutamate clearance</td>
<td>De Felice et al., 2014</td>
</tr>
<tr>
<td></td>
<td>miR-142-5p</td>
<td>Upregulated in spinal cord of sALS patients</td>
<td>Regulates neuronal homeostasis and neurodegeneration-related transcripts</td>
<td>Figueroa-Romero et al., 2016</td>
</tr>
<tr>
<td></td>
<td>miR-140-3p, miR-577, let-7e, miR-148-5p, miR-133b, miR-140-3p, miR-577</td>
<td>Downregulated in spinal cord of sALS patients</td>
<td>Regulates neuronal homeostasis and neurodegeneration-related transcripts</td>
<td>Figueroa-Romero et al., 2016</td>
</tr>
<tr>
<td>Huntington’s disease</td>
<td>miR-9, miR-9*</td>
<td>Downregulated in HD patient cortex</td>
<td>Affects REST and CoREST binding</td>
<td>Packer et al., 2008</td>
</tr>
<tr>
<td></td>
<td>miR-10b-5p</td>
<td>Upregulated in HD prefrontal cortex</td>
<td>Predicted to affect nervous system development and transcriptional regulation pathways</td>
<td>Hoss et al., 2015</td>
</tr>
<tr>
<td></td>
<td>miR-22</td>
<td>Downregulated in HD brains</td>
<td>Predicted regulation of HDAC4, RCOR1, RGS2</td>
<td>Jovicic et al., 2013</td>
</tr>
<tr>
<td></td>
<td>miR-34b</td>
<td>Upregulated in plasma of presymptomatic HD</td>
<td>Mediates protective effect on mutant HTT</td>
<td>Gaughwin et al., 2011</td>
</tr>
<tr>
<td></td>
<td>miR-132</td>
<td>Downregulated in HD frontal cortex</td>
<td>Predicted to affect neurite growth and neuronal connectivity via p250GAP (ARHGAP32) mRNA</td>
<td>Johnson and Buckley, 2009</td>
</tr>
</tbody>
</table>

There are many dysregulated miRNAs in different neurodegenerative diseases. Listed here are the dysregulated miRNAs that are dysregulated as identified in human tissue, along with the mechanisms of action. sALS and fALS, sporadic and familial ALS, respectively. miR-9 and miR-9* are two different miRNAs.

Charcot–Marie–Tooth, a disease of peripheral neuropathy (Antonellis et al., 2003; Nangle et al., 2007; Xie et al., 2007). It is unclear why abnormalities in tRNA biogenesis result in different peripheral neuropathies but various mechanisms have been proposed, including: (1) loss of function of tRNA loading and subsequent protein translation inhibition; (2) a dominant-negative effect whereby mutant protein interferes with the wild-type protein activity; and (3) impaired axonal transport due to tRNA synthetase mutations, among others (Motley et al., 2010; Niehues et al., 2015). A mutation in CLP1 (R140H) is a cause of progressive brain atrophy.
and microcephaly in humans (Karaca et al., 2014; Schaffer et al., 2014). CLP1 R140H renders CLP1 unable to interact with TSEN, resulting in altered tRNA processing (see poster panel D). Mutations in ANG that might contribute to the loss of ANG function also occur in ALS (Greenway et al., 2004, 2006; Wu et al., 2007b). Altered translation can also contribute to neurodegenerative disease. Specifically, a mutation in GTPBP2, which encodes a ribosome rescue factor, leads to global ribosomal stalling by epistatically interacting with an isodecoder of nuclear-encoded tRNAs, called n-Tra20. This aberrant interaction ultimately leads to neurodegeneration via altered translation (Ishimura et al., 2014). These studies only provide a snapshot of how aberrations in tRNA processing can lead to neurodegeneration.

IncRNAs have also been implicated in neurodegenerative diseases (see poster panel E). These RNAs are longer than 200 nucleotides and fulfill various functions, including acting as scaffolds for chromatin modifiers and nuclear paraspeckles, as transcriptional co-regulators, and even as decoys for other RNAs (Prensner and Chinnaiyan, 2011). Alterations in IncRNAs can affect any one of these processes, thereby contributing to neurodegeneration. IncRNAs associated with disease can post-transcriptionally increase gene expression, as seen with the IncRNAs, BACE1-antisense (AS) and Inc-SCA7 (official symbol ATXN7L3B). BACE1-AS is increased in AD brains and competes with miRNA-545-5p binding to stabilize BACE1 mRNA. This is associated with increased BACE1 expression and with the formation of the Aβ peptides that contribute to AD pathology (see poster panel E) (Faghihi et al., 2008). In spinocerebellar ataxia type 7 (SCA7), mutant CAG repeats in the ATXN7 gene contribute to cerebellar neuronal death. Normally, ATXN7L3B regulates ATXN7, which is loaded into a transcriptional activator complex, called STAGA. STAGA promotes miR-124 biogenesis, which in turn, represses ATXN7L3B expression. In SCA7, mutant CAG repeats promote mutant ATXN7 protein levels, which reduce STAGA activity. This consequently reduces miR-124 biogenesis, increases ATXN7L3B expression and promotes more mutant ATXN7 production (Tan et al., 2014). Other examples of genes with altered IncRNAs include MALAT1 and NEAT1, which are important for splicing and synapese formation (Bernard et al., 2010; Tripathi et al., 2010). Both of these RNAs are bound by TDP-43 and FUS (Lagier-Tourenne et al., 2012; Polymenidou et al., 2011; Tollervey et al., 2011). MALAT1 and NEAT1 have been shown to colocalize in nuclear paraspeckles, sites where RNA is retained to control gene expression during different cell processes (see poster panel E) (Fox and Lamond, 2010). Additionally, NEAT1 is upregulated in the HD brain, which is thought to make cells susceptible to oxidative stress (Johnson, 2012; Sunwoo et al., 2016). Other HD-associated genes with IncRNAs include TUG1, which is increased in HD and which normally associates with polycomb repressive complex 2 (PRC2) to repress gene expression (Johnson, 2012; Khalil et al., 2009) (see poster). Thus, IncRNAs are likely to influence gene expression post-transcriptionally to contribute to neurodegenerative disease.

Therapies designed to target IncRNAs involve inhibiting the function of IncRNAs usually by: (1) blocking the interaction of the antisense and sense mRNA by degrading the antisense strand, which leads to the transcriptional repression of the gene; (2) using aptamers to bind and inhibit IncRNA structures and prevent their activity; and (3) employing small molecules that inhibit IncRNA interactions (Fatemi et al., 2014; Sullenger and Nair, 2016). Although it has been shown that treating a mutant APP-expressing human HEK-SW cell line with siRNA against BACE1-AS leads to reduced Aβ (Faghihi et al., 2008), this finding has not been validated in an AD mouse model or human patients. A better understanding of how specific IncRNAs contribute to the disease phenotype is integral to designing better-targeted therapeutics for these diseases.

Conclusions

Neurodegenerative diseases occur by different means and present with various pathologies. However, it is becoming increasingly clear that altered or defective RNA metabolism, including mislocalized RBPs and aberrant mRNA biogenesis or expression, can contribute to neurodegeneration. Because numerous disease-associated pathways are perturbed in these neurodegenerative diseases (as summarized in the accompanying poster), it is unlikely that targeting only one of these modalities will lead to a complete cure. Nonetheless, reversing some of these RNA aberrations could prove to be effective in modifying the incessantly downward disease trajectory associated with these diseases. Perhaps by modifying disease progression, such approaches could provide a significant benefit for those afflicted by neurodegenerative disease.

This article is a special subject collection ‘Neurodegeneration: from Models to Mechanisms to Therapies’, which was launched in a dedicated issue guest edited by Aaron Gitler and James Shorter. See related articles in this collection at http://dmm.biologists.org/collection/neurodegenerative-disorders.

Acknowledgements

We thank members of the Lee lab for critical reading of the manuscript.

Competing interests

The authors declare no competing or financial interests.

Funding

Work in the authors’ labs is supported by the National Institutes of Health (1R01NS056793-01 to E.B.L. and 4T32AG000255-19 to E.Y.L.).

At a glance


References

Batra, R., Charizanis, K., Manchanda, M., Mohan, A., Li, M., Finn, D. J., Goodwin, M., Zhang, C., Sobczak, K., Thornton, C. A. et al. (2014). Loss of


