Widespread intron retention impairs protein homeostasis in C9orf72 ALS brains

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Abstract

The GGGGCC hexanucleotide expansion in *C9orf72* (C9) is the most frequent known cause of Amyotrophic Lateral Sclerosis (ALS) and Frontotemporal Dementia (FTD), yet a clear understanding of how C9 fits into the broader context of ALS/FTD pathology has remained lacking. The repetitive RNA derived from the C9 repeat is known to sequester hnRNP H, a splicing regulator, into insoluble aggregates, resulting in aberrant alternative splicing. Furthermore, hnRNP H insolubility and altered splicing of a robust set of targets have been observed to correlate in C9 and sporadic ALS/FTD patients alike, suggesting that changes along this axis are a core feature of disease pathogenesis. Here, we characterize previously uncategorized RNA splicing defects involving widespread intron retention affecting almost 2,000 transcripts in C9ALS/FTD brains exhibiting a high amount of sequestered, insoluble hnRNP H. These intron retention events appear not to alter overall expression levels of the affected transcripts, but rather the protein coding regions. These retained introns affect transcripts in multiple cellular pathways predicted to be involved in C9 as well as sporadic ALS/FTD etiology, including the proteasomal and autophagy systems. The retained intron pre-mRNAs display a number of characteristics, including enrichment of hnRNP H-bound splicing enhancer motifs and a propensity for G-Q formation, linking the defective splicing directly to high amounts of sequestered hnRNP H. Together, our results reveal previously undetected splicing defects in high insoluble hnRNP H-associated C9ALS brains, suggesting a feedback between effective RNA binding protein dosage and protein quality control in C9, and perhaps all, ALS/FTD.

Introduction

C9orf72 (C9) is a critical gene at the intersection of the devastating neurodegenerative diseases Amyotrophic Lateral Sclerosis (ALS) and Frontotemporal Dementia (FTD). Expansion of the variable length hexanucleotide repeat contained within the first intron of C9 is the most common known genetic lesion in both familial and sporadic forms of ALS (DeJesus-Hernandez et al. 2011; Renton et al. 2011), although a large majority of ALS cases have no known mutation. Moreover, C9 repeat expansion exhibits the perplexing behavior of causing FTD in addition to, or instead of, ALS, differing even amongst family members with the same parental allele. It is widely believed that the ability to explain, and eventually treat, the ALS/FTD disease spectrum as a whole will stem from a precise mechanistic understanding of how this polymorphic mutation sets off a cascade ending in highly specific neuronal degeneration (Cook and Petrucelli 2019). To this end, studies seeking to understand the basic molecular properties of the C9 repeats, and to find similarities between C9ALS/FTD and sporadic ALS/FTD, have highlighted an important role for pre-mRNA splicing and its dysregulation (Taylor et al. 2016; Conlon et al. 2018; Nussbacher et al. 2019). RNA splicing is a highly complex process that is known to distinguish neuronal subtypes (Furlanis et al. 2019), thereby suggesting a potential mechanism for the differing cellular vulnerabilities to a ubiquitously expressed somatic mutation.

In the broad interest of identifying a central mechanism of ALS/FTD through consideration of all genetic causes, defects in pre-mRNA processing, resulting from alterations in the activity of RNA binding proteins (RBPs) (Conlon and Manley 2017), and inadequate protein degradation mechanisms (Blokhuis et al. 2013), through the autophagy pathway (Ramesh and Pandey 2017), have come to the forefront (Ito et al. 2017). Moreover, it has been speculated that the two processes synergize, potentially reinforcing one another in a vicious cycle (Ito et al.

2017). For instance, defects in autophagy and related protein clearance pathways may lead to an overabundance of phase-separated condensates of RBP-rich ribonucleoprotein granules, which may mature into fibril-like RNP aggregates. Another idea is that mis-localization and/or aggregation of RBPs due to genetic mutation may put strain on the protein clearance pathways of the cell. In either scenario, altered or diminished RBP function would lead to mRNA expression and processing changes, for instance through aberrant alternative pre-mRNA splicing. Evidence has been put forth suggesting that detectable splicing changes may preferentially affect transcripts encoding RBPs, reinforcing their intrinsic ability to aggregate and thereby perpetuating this endless cycle (Conlon et al. 2018; Deshaies et al. 2018). Along this theme, splicing defects occurring within transcripts that encode components of the protein degradation machinery may compound the RBP aggregation that is upstream of splicing changes. While this is an interesting idea, no evidence to suggest that such genes are particularly susceptible to altered gene expression programs has been presented.

We initiated this study with the aim of extending previous results that documented genome-wide changes in pre-mRNA splicing in ALS/FTD patient brains. Specifically, we detected a direct correlation between extent of insolubility of the splicing regulatory RBP hnRNP H, and other RBPs, and degree of missplicing, in both C9 and sporadic samples (Conlon et al. 2018). Here we wished to focus on whether this correlation was maintained with an independent, more stringent method of AS analysis in C9 patient brains, to determine whether specific types of AS events, such as intron retention, were especially prevalent, and to investigate whether misspliced transcripts reflect specific biological pathways.

Results

We previously characterized extensive pre-mRNA missplicing events in C9 ALS/FTD patient brains, and found that the extent of dysregulated splicing correlated with the levels of sequestered, insoluble hnRNP H (Conlon et al. 2016; Conlon et al. 2018). To investigate these aberrant splicing patterns further, we first compared the global alternative splicing (AS) profiles in post-mortem cerebellum samples from normal controls and from C9 ALS/FTD patients (Table 1). Two sub-categories of C9 samples were compared to the controls based on the level of hnRNP H aggregation, as defined by Conlon et al. (Conlon et al. 2018), in order to stratify sporadic ALS/FTD: those with high insoluble hnRNP H (above 80%; C9high) and those with relatively low levels of insoluble hnRNP H (below 60%; C9low; Table 1). We used the software tool Junction Usage Model (JUM) (Wang and Rio 2018) for differential AS analysis. JUM provides two important advantages compared to other software tools in that it does not rely on any prior knowledge of transcriptome or splicing event annotations and is thus suitable for tissues like the brain where previously unknown splicing events are prevalent, and it also performs stringent intron retention analysis with very low false positive rates (Wang and Rio 2018).

We first analyzed splicing patterns in RNA samples isolated from C9high brains and from controls. A total of 4,681 significantly differentially spliced AS events (q-value ≤ 0.1; $\Delta\Psi \geq$ 10%) were identified by JUM (Fig. 1A; upper panel). 75% of these events were intron retention (IR) events, indicating a more general deficiency in splicing in these patients, beyond only changes in AS (Fig. 1A; upper panel). In contrast, we found that there were no significant differences in splicing between the C9low brain samples and controls (Fig. 1A; lower panel), consistent with our previous results (Conlon et al. 2016; Conlon et al. 2018) and indicating that widespread intron splicing deficiency is highly correlated with the extent of hnRNP H

sequestration. We note that this significant elevation in IR in C9high samples was not observed in our previous study (Conlon et al. 2018), which used the AS analysis tool LeafCutter (Li et al. 2017) with the same samples. Although LeafCutter is also annotation free, it does not detect IR (Li et al. 2017).

We next characterized the altered IR events in more detail. Among the 3,177 significantly changed IR events, we found that 2,986 introns (94%) were more retained in C9high patients (Fig. 1B, D and E). Among them, 621 introns displayed elevated IR levels of more than 25% in C9high samples compared to normal controls. Both the direction and magnitude of change were, in general, consistent across all C9high patient samples (Fig. 2A). We next investigated how these elevated retained introns affected accumulation of the transcripts containing them. Previous reports suggested that IR can lead to decreased expression of the affected gene through nonsense-mediated decay (NMD), due to a premature stop codon introduced within the retained intron (Ge and Porse 2014; Jacob and Smith 2017). Among the 1,944 genes with significantly elevated retained introns in C9high brains, only 11 (0.6%) displayed significant decreases (q-value ≤ 0.1; fold change ≥ 1) in transcript levels, and the magnitude of down-regulation was relatively small, mostly around 1-2 fold (Fig. 2B). This strongly suggests that the prevalent elevated IR in C9high brains does not affect the overall expression levels of the relevant genes.

We then investigated whether the significantly elevated retained introns in C9high brains possess any unique features compared to other introns in general. We found that the retained introns tend to have a smaller size (median 602 nt versus 1,793 nt for all introns detected in the brain samples, and 819 nt for the introns that are more retained in the normal controls) (Fig. 2C). In addition, these introns have significantly higher G/C content (Fig. 2D), and relatively weaker

5' and 3' splice site (Supplemental Fig S1B, S1C), suggesting that they have higher dependence on accessory splicing factors, such as hnRNP H.

We next compared overall levels of gene expression, independent of retained introns, between C9 patient samples and normal controls. We found only a relatively small number of genes (731) that displayed significant expression level changes between C9high and controls (mostly ~2 fold change) (Supplemental Fig S2A, Supplemental Fig S2C). Similar to the differential AS analysis, there were almost no differences in gene expression profiles between C9low samples and normal controls (Supplemental Fig S2B). This latter result indicates that the presence of an expanded C9 allele is not sufficient to cause changes in gene expression in the absence of measurable RBP insolubility. Also, the small number and magnitude of changes in the C9high samples are consistent with the idea that hnRNP H and related RBP insolubility (Conlon et al. 2018) affects primarily splicing and not transcription and/or mRNA stability. Extending the comparison, only 24 out of the 631genes showing reduced expression overlapped with the set of 2,927 genes that displayed significant differential AS (Supplemental Fig S2D)

We next analyzed whether genes whose transcripts displayed elevated IR in C9high brains were enriched in specific functional pathways, using Gene Ontology analysis (p-value $<10^{-3}$). We noticed that the retained introns are found in transcripts functionally enriched in many ALS-implicated pathways (van Blitterswijk and Landers 2010; Arnold et al. 2013; Blasco et al. 2014; Kim and Taylor 2017; Webster et al. 2017), including the protein aggregation/misfolded protein clearance pathways (Blokhuis et al. 2013; Cirulli et al. 2015; Webster et al. 2017), protein transport control pathways (Kim and Taylor 2017), and pre-mRNA splicing regulatory pathways (Conlon et al. 2016) (Fig. 3A). The fact that transcripts encoding proteins involved in pre-mRNA splicing also displayed intron retention raises the possibility that

some splicing defects could be secondary to the events that are due to direct sequestration of RBPs such as hnRNP H, as discussed previously (Conlon et al. 2018).

Both of the two major protein quality control pathways required for cellular homeostasis were affected: the ubiquitin-proteasome pathway (Deng et al. 2011) and the autophagy pathway (Dikic 2017) (Fig. 3A and B, left and middle panels). Both of these pathways have been implicated in ALS pathology, because compromised protein quality control can contribute to accumulation of protein aggregates, a hallmark of ALS-diseased neurons (Blokhuis et al. 2013). For the proteasome pathway, elevated IR has the potential to affect almost all categories of the protein subunits that assemble and maintain the function of the proteasome machinery (Fig. 3B; Supplemental Fig S3-S12; Table 2; Supplemental Table S1). Most of the retained introns are predicted to change either partially or completely the C termini of the encoded proteins (PSMA3, PSMC3, PSME1, for example; Table 2; Supplemental Table S1; Supplemental Fig S3-S12). In one extreme case (PSMA4), IR has the potential to produce an entirely distinct protein, because the retained intron, which contains a significant open reading frame (ORF), resides before the authentic ORF (Table 2; Supplemental Table S1). As a result, these C9high-associated IR events can have significant effects on the integrity and function of the proteasome machinery. For example, the C terminus of PSMA3, which would be significantly affected by IR, is known to be an interaction hub for certain intrinsically disordered proteins, functioning to facilitate their degradation (Sanchez-Lanzas and Castano 2014). IR thus potentially compromises degradation of such proteins.

We next wished to gain more insight into the basis for the greatly increased IR in C9high patients. Specifically, is this elevated IR mechanistically linked to the sequestration level of hnRNP H. HnRNP H is known to bind to NGGG(+)N (3 or more consecutive guanines) motifs

downstream of a 5' splice site in the intronic region (Caputi and Zahler 2001; Wang and Cambi 2009; Xiao et al. 2009; Uren et al. 2016). These poly(G) motifs typically act as Intronic Splicing Enhancers (ISEs), meaning that when hnRNP H binds to these motifs, it enhances splicing of the intron (Caputi and Zahler 2001; Wang and Cambi 2009; Xiao et al. 2009; Uren et al. 2016). We thus first calculated and compared the enrichment of NGGGN elements in three intron groups: introns that were significantly more retained in C9high patients compared to normal controls (Fig. 4A, red), the much smaller number of introns that were instead significantly more retained in the controls (Fig. 4A, blue), and all introns detected in the patient brain samples (Fig. 4A, gray). We found that introns that were more retained in C9ALS patients were significantly more likely to contain NGGGN elements within 100 nts downstream of the 5' splice sites compared to total introns (Fig. 4A; Mann-Whitney *U* test p-value $< 10^{-16}$). In contrast, introns that were more retained in the normal controls are deficient in such poly(G) motifs (Fig. 4A; Mann-Whitney *U* test p-value $< 10^{-8}$). Moreover, enrichment for the NGGGN motif was especially prominent within 10-40 bp downstream of the 5' splice site in the C9ALS retained introns (Fig. 4A), matching the previously reported general locations of hnRNP H-associated ISEs in introns (Xiao et al. 2009). These results strongly suggest that the splicing of the C9ALS-retained introns tends to have higher dependency on hnRNP H and consequently will be more vulnerable in C9high ALS samples where the levels of soluble, functional hnRNP H is significantly reduced (Conlon et al. 2016).

We next examined subcategories of C9ALS-elevated retained introns, in the proteasome, autophagy, and splicing regulatory pathways. We again observed enrichment of the NGGGN motif relative to general introns, with the highest enrichment in the proteasomal pathway (Fig.

4A). This suggests that splicing of transcripts encoding components of the protein quality control pathway tends to be more susceptible to the reduced hnRNP H levels in C9high ALS brains.

The strength of hnRNP H binding to the NGGG(+)N motifs and the corresponding enhancement of the intron involved is further determined by the length of the G-tract in the poly(G) run motif (Caputi and Zahler 2001; Wang and Cambi 2009; Xiao et al. 2009; Uren et al. 2016). We therefore next examined possible enrichment of longer (four consecutive guanines or more) G tracts in different intron groups (Fig. 4B). In accordance with the results above, we indeed observed significant enrichment of longer G tracts in introns that were more retained in C9ALS patient brain samples (Fib. 4B; Mann-Whitney *U* test p-value < 10^{-10}). We also observed that a significantly smaller fraction of introns that were more retained in control brains possess long G tracts in poly(G) motifs (Fig. 4B; Mann-Whitney *U* test p-value < 10^{-18}).

It is also possible that hnRNP H protein can bind to several poly(G) motifs in a cooperative manner. As a result, having multiple poly(G) tracts near the 5' splice site in the intron can lead to the coordination of multiple hnRNP H proteins and as a result stronger enhancement of splicing of the intron. Moreover, when four or more poly(G) runs are in close proximity they can fold into RNA G-quadruplexes (G-Qs), and these highly stable structures may preclude binding of general splicing factors, such as U1 snRNP (Tan et al. 2019). Proteins that have high affinity for individual poly(G) motifs, like hnRNP H, may play important roles in blocking structure formation (Guo and Bartel 2016), and their sequestration may lead to especially severe splicing defects in introns that have G-Q potential. We thus also calculated and compared enrichment of multiple (four or more) non-overlapping poly(G) run elements in the vicinity of 5' splice sites in the different intron groups (Fig. 4C). We again observed enrichment of multiple, non-overlapping poly(G) motifs in introns that were significantly more retained in

C9high samples, especially in the protein quality control pathway-associated genes (Fig. 4C; Mann-Whitney *U* test p-value $<10^{-18}$). While these criteria are indicators of potential structure formation, sequence-based prediction of G-Q existence is quite complicated due to the presence of competing RNA structures (Wang et al. 2019). Thus, while we conclude that the retained introns are more likely to contain multiple poly(G) motifs in the immediate downstream intron, further experimental analysis would be needed to show that G-Q formation occurs at these sites.

Finally, to provide in vivo support for the hnRNP H binding motif analyses described above, we examined whether empirically determined hnRNP H binding events are enriched in affected retained introns in the vicinity of their 5' splice sites. We profiled hnRNP H binding sites from a previously published hnRNP H CLIP-seq dataset that utilized HEK 293T cells (Katz et al. 2010) and compared the enrichment of hnRNP H peaks (B-H corrected p-value < 0.05) in the vicinity of 5' splice sites in different intron groups (Fig. 5). Overall, a relatively small fraction of the introns detected in patient cerebellum had HEK 293T-derived hnRNP H CLIP peaks. This could be a function of several factors, for instance the low-sequencing depth and lack of concordance in overall gene expression profiles between human adult cerebellum and HEK 293T cells. Nonetheless, we indeed observed significant enrichment of hnRNP H binding sites within 100 nts downstream of the 5' splice sites in introns that were more retained in C9ALS patients (Fig. 5; Mann-Whitney *U* test p-value $< 10^{-17}$), while introns that were more retained in the normal controls were deficient in hnRNP H binding sites (Fig. 5; Mann-Whitney *U* test p-value $<10^{-19}$). Together, these and the above results further suggest that the C9ALS retained introns tend to be more dependent on hnRNP H-mediated regulation and thus more sensitive to the reduction in functional hnRNP H levels in the C9high ALS patient brains.

Discussion

Recent advances in the molecular genetics of ALS and FTD have pointed to a convergence of protein clearance pathway dysfunction, RBP aggregation and RNA processing defects (Ito et al. 2017). However, despite this growing consensus (Ito et al. 2017; Cook and Petrucelli 2019) and the increased availability of transcriptomic data (Prudencio et al. 2015; Conlon et al. 2018), an outstanding challenge that remains is how to identify the most central and meaningful gene expression changes that potentially drive the disease phenotype. A drawback of any transcriptomic analysis involving human patients is that the standard assumption is to compare patients to unaffected controls. In doing this, any meaningful variability between patients can be grossly underestimated and skew the outcome. Furthermore, computational analyses done with different algorithmic methods can lead to vastly different results, as evidenced by the differences we have observed using JUM and LeafCutter (Conlon et al. 2018). In this manuscript, we have carefully considered both of these factors. Through our use of functional stratification of C9ALS/FTD patients by hnRNP H insolubility, and through the use of the intron-aware method JUM (Wang and Rio 2018), we have identified an important prevalence of IR events in proteasomal genes that may have otherwise been overlooked in different analyses (Prudencio et al. 2015; Conlon et al. 2018). Furthermore, our data illustrate how defects in the proteasome can potentially be both cause and consequence of dysregulated splicing programs in C9 ALS/FTD, synergizing with what is known about proteostasis effects in C9 and other forms of ALS and FTD.

Intron retention is a particular form of alternative splicing that has been previously associated with human disease. It has been observed for example in some cancers (Dvinge and Bradley 2015) as well as in ALS (Luisier et al. 2018; Humphrey et al. 2020). Perhaps more than

other forms of alternative splicing, intron retention has the ability to explain the subtle accumulation of defective transcripts, leading to dysregulated protein expression even in cases where mutations in the relevant genes are strongly selected against. For instance, while mutations affecting proteasomal subunits directly may have the potential to recapitulate some aspects of ALS/FTD, they may be too severe to allow viability, or may lead to other deleterious consequences before the onset of ALS/FTD at later stages in life. Indeed, few genes encoding proteasome subunits have been shown to be mutated in disease (Gomes 2013). In contrast, through our comprehensive analysis of IR in stratified C9 patient samples, we have found evidence for pervasive defects in transcripts encoding proteasomal subunits.

Evidence has existed for some time that defects in the ubiquitin-proteasome system (UPS) play a significant role in ALS/FTD pathology (Bendotti et al. 2012). This is not only reflected in mutations in the *UBQLN2* gene (Deng et al. 2011) that are found in a fraction of ALS/FTD patients, but evidence for UPS defects have been observed widely in ALS/FTD, including in sporadic cases (Kabashi et al. 2012). However, apart from *UBQLN2* mutations, the basis for UPS dysfunction has been largely unknown. Our results that defects in splicing, specifically IR, of transcripts encoding multiple UPS subunits offers an explanation, at least in C9 patients displaying high levels of hnRNP H insolubility. The concept that an individual RBP can regulate a set of functionally coherent transcripts has been demonstrated previously, as in the case of the neuronal RBP Nova (Ule et al. 2003).

It has recently been shown that poly Gly-Ala dipeptide repeat proteins, which can be produced by repeat-associated non-AUG (RAN) translation of the C9 GGCCCC repeats, can form aggregates that interact with 26S proteasomes and disrupt their activity (Guo et al. 2018). Thus, it may be in C9 ALS/FTD, affected neurons suffer from a two-pronged attack on the UPS

system, reflecting both missplicing and RAN translation. In addition, while our study dealt with C9 samples, our recent work showed that a significant fraction of sporadic ALS/FTD brains display high levels of hnRNP H aggregation and extensive missplicing (Conlon et al. 2018). Thus, it is possible that missplicing, including IR, contributes to the defect in the UPS observed in sporadic as well as C9 ALS/FTD.

Although we have focused heavily on hnRNP H, it should be mentioned that we previously observed levels of insoluble hnRNP H to be highly correlated to the insolubilities of several other ALS/FTD-relevant RBPs, such as TDP-43 and FUS (Conlon et al. 2018). While we have argued that hnRNP H is a driver of such "multi-RBP proteinopathy," we cannot rule out the possibility that the other proteins that display this highly insoluble behavior contribute to splicing changes and could be used to functionally stratify this patient group in a similar manner. Nonetheless, as we have carefully measured hnRNP H insolubility values across a wide range of patients, it is the most reliable metric we have to describe this relationship. Similar to our previously reported findings on splicing in C9 and sporadic ALS/FTD (Conlon et al. 2018), quantifiable changes in IR were detected only in patients with high hnRNP H insolubility (C9high). As discussed previously (Conlon et al. 2018), it may be that the samples with lower measurable insolubility also undergo similar changes in splicing, including IR, but that due to the smaller magnitude of these changes, or their presence in only certain cell populations, they fail to pass stringent filters set to identify significant changes relative to controls. This argument makes further sense in light of the 'vicious cycle' we propose is at play here. Given that RBP aggregation leads to these splicing changes, and the splicing changes affect the cell's ability to clear them, we anticipate a strong compounding effect, where the initial amount of RBP aggregation is amplified through IR and resultant proteasomal dysfunction. Indeed, this may

complement or exacerbate another vicious cycle we proposed previously, in which the extensive missplicing of transcripts encoding splicing regulatory RBPs that occurs in C9high brains leads to altered levels of these proteins, which in turn causes additional missplicing.

In conclusion, our analyses have shed new insights into the complex, interconnected relationship between RNA processing defects and protein-clearance pathways in ALS/FTD, highlighting the ways in which they may mutually reinforce the pathological events that culminate in this devastating disease spectrum.

Methods

Human patient samples

Patient brain samples used in this study are identified according to previously published conventions (Conlon et al. 2018). All human samples were donated for research purposes by next of kin. See detailed patient sample information in Table 1.

RNA-seq data

Previously published RNA-seq data (Conlon et al. 2018) was downloaded from GEO accession GSE116622.

RNA-seq data mapping for JUM

RNA-seq reads were mapped to the human (hg38) genomes using STAR (Dobin et al. 2013). A 2-pass mapping mode was applied for read alignment, which has been shown to greatly improve splice junction quantification. The detailed mapping commands and procedures are listed in the JUM manual: https://github.com/qqwang-berkeley/JUM/wiki/0.b.-Input-files (Wang and Rio 2018). After that, only uniquely mapped reads were kept in the output for downstream JUM analysis.

Running JUM on the RNA-seq samples

JUM (version 2.0.2) was run on the RNA-seq samples. Each patient sample in normal control, C9high and C9low categories is treated as a biological replicate when comparing the overall alternative splicing profile across different conditions. JUM commands are run as detailed in the JUM manual: https://github.com/qqwang-berkeley/JUM/wiki/3.1.-Manual-running-JUM-(v2.0.2-and-up) (Wang and Rio 2018). Statistical cutoff of qvalue ≤ 0.1, ΔΨ or ΔPSI ≥ 10% is applied to the differential alternative splicing analyses described in this study. A detailed summary of differentially alternatively spliced events between normal controls and C9high samples in six AS categories (cassette exon, A5SS, A3SS, IR, mutually exclusive exons, and composite) are in Supplemental Data S1-S6.

Intron property analysis

GC content in introns was calculated using the nuc option in BEDTools (https://bedtools.readthedocs.io/en/latest/) (Quinlan 2014). The strength of 5' splice sites and 3' splice sites of the introns were calculated using MaxEntScan (http://hollywood.mit.edu/burgelab/maxent/Xmaxentscan_scoreseq.html) (Yeo et al. 2004). The seqkit was used to count occurrence of poly(G) motifs in introns and their locations (https://bioinf.shenwei.me/seqkit/) (Shen et al. 2016).

Visualization

All RNA-seq track data and junction reads were visualized using IGV (Robinson et al. 2011) and the Sashimi plots tool (Katz et al. 2015). Visualized tracks were further organized using ImageJ (Schneider et al. 2012). All boxplots in this paper were plotted using BoxPlotR (Spitzer et al.

2014). Volcano plots in this paper were plotted using R (Team 2019) and ggplot2. Heatmaps in this paper were plotted using R (Team 2019) and heatmap.2.

Gene Ontology analysis

Gene Ontology analyses were performed using GORILLA (http://cbl-gorilla.cs.technion.ac.il/) (Eden et al. 2009). A list of transcripts expressed in the normal control brains at greater than 10 reads was used as a background data set.

Differential gene expression analysis between C9ALS and normal control patient brain samples

Differential gene expression analysis between C9ALS patient samples and the normal control samples were performed using DESeq2 (Love et al. 2014). The read to gene count was calculated using the multicopv option in BEDTools (Quinlan 2014). After that, DESeq2 was run on the RNA-seq samples as described in the manual: http://bioconductor.org/packages/devel/bioc/vignettes/DESeq2/inst/doc/DESeq2.html.

A detailed summary of differentially expressed genes between normal controls and C9high samples, as well as between normal controls and C9low samples are listed in Supplemental Data S7 and S8, respectively.

Analysis of hnRNP H CLIP-seq data

HnRNP H CLIP-seq datasets were download from (Katz et al. 2010) (GSE23694). Processing of the datasets as well as hnRNP H binding peak calling were done using the CTK software tool (Shah et al. 2017), following the protocol as described in https://zhanglab.c2b2.columbia.edu/index.php/CTK_Documentation.

Competing Interests Statement

The authors have no competing interests.

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Main Figures and Table legends:

Figure 1. Widespread, elevated intron retention is observed in C9high patient brain samples. (A) number of significantly differentially spliced AS events in six AS categories comparing C9high patient samples with normal controls, and C9low patient samples with normal controls, respectively. (B) Volcano plot showing the magnitude and direction of changes in intron retention for a total of 3,177 changed intron retention events between C9high patient samples and normal controls. x-axis showing the difference of intron-retained isoform levels between normal controls and C9high patient samples. (C) Volcano plot showing the magnitude and direction of changes in intron retention between C9low patient samples and normal controls. (D) and (E) Sashimi plot and genome browser shots for two significantly elevated intron retention events in two gene transcripts, hnRNPH1 and PSMA3. Exon coverage from RNA-seq data is shown in three normal control samples (blue) and three C9high samples (red); arcs represent splice junctions identified from the RNA-seq data and the number of uniquely mapped RNA-seq reads mapped to the junctions are shown across the arc; human annotation (hg38) of the transcripts is shown at the bottom. The black arrow indicates the direction of the promoter. The dotted lines indicate the region of the transcript that is enlarged to highlight the retained intron region.

Figure 2. Prevalent, elevated intron retention in C9high patient samples does not change overall gene expression levels of the affected transcripts. (A) Heatmap of the changed intron retention levels for 3,177 introns (column), comparison across six normal control samples and six C9high patient samples. Magnitude and direction of

changes in intron retention between normal controls and C9 samples are color-coded. (B) Volcano plot showing the overall expression level changes in genes that undergo significantly elevated intron retention. X-axis showing fold changes in gene expression level between normal controls and C9high patient samples. (C) Boxplot showing intron length distribution between introns that are more retained in C9high patient samples, introns that are more retained in normal controls, and all introns detected in the brain samples. (D) Boxplot showing intron CG content comparison between introns that are more retained in C9high patient samples, introns that are more retained in normal controls, and all introns detected in the brain samples.

Figure 3. Transcripts that undergo significantly changed intron retention in C9high patient samples encode proteins functionally enriched in cellular protein quality control pathways. (A) Gene Ontology enrichment analysis of transcripts that undergo significantly changed intron retention in C9high patient samples compared to normal controls. (B) Volcano plots showing the magnitude and direction of changes in intron retention for introns embedded in transcripts that encode proteins functioning in the proteasomal pathway, the autophagy pathway and the splicing regulatory pathway, respectively.

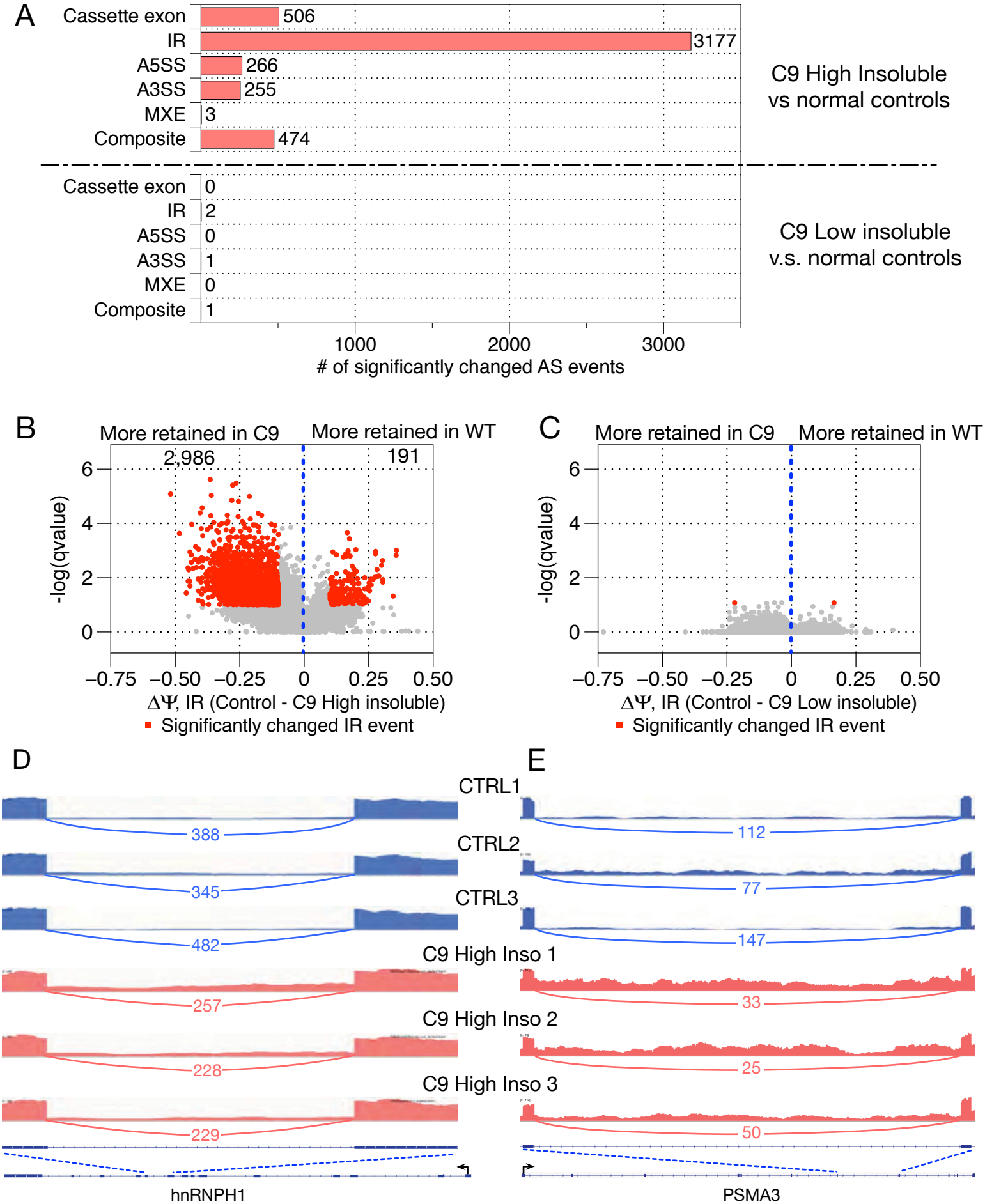
Figure 4. Introns that are significantly more retained in C9high patient samples are enriched in hnRNP H-associated intronic splicing enhancer motif activities. (A) Cumulative distribution function plot showing the fraction of introns with at least one NGGG+N motifs at the designated intronic position (bp) downstream of the 5' splice site (X axis showing a total of 0-100 bp downstream of the 5' splice site) for six groups of

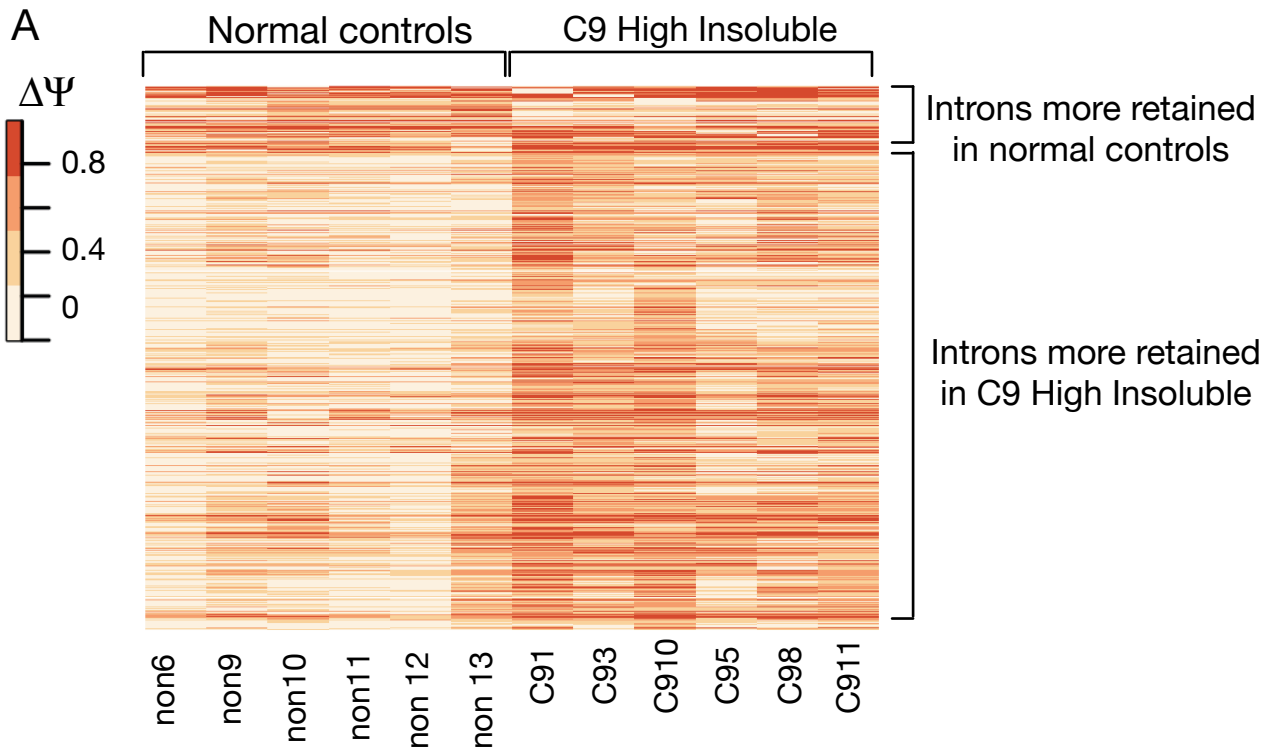
introns. (B) Cumulative distribution function plot showing the fraction of introns with at least one NGGG+N motifs of 4 and more Gs in the poly(G) tract at the designated intronic position (bp) downstream of the 5' splice site for six groups of introns. (C) Cumulative distribution function plot showing the fraction of introns with at least four non- overlapping NGGG+N motifs at the designated intronic position (bp) downstream of the 5' splice site for six groups of introns.

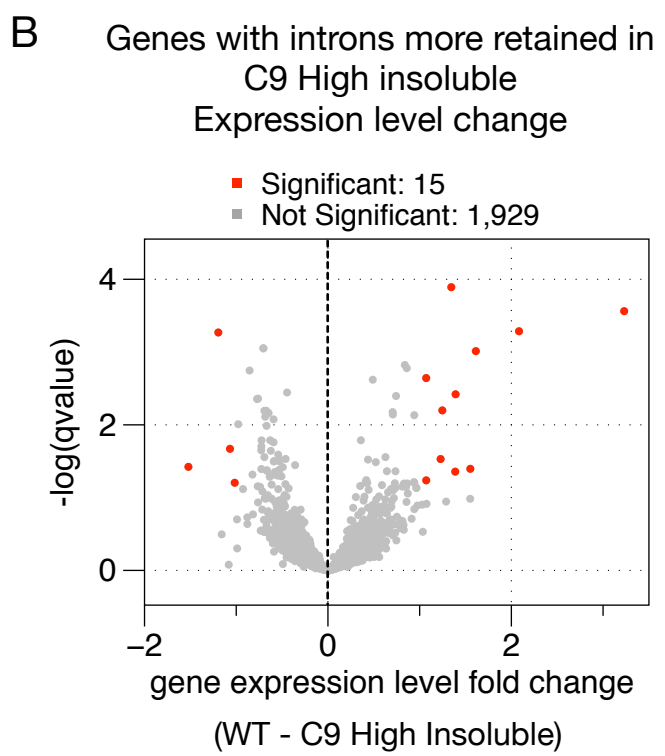
Figure 5. Cumulative distribution function plot showing the fraction of introns with at least one hnRNP H binding sites at the designated intronic position (bp) downstream of the 5' splice site (X axis showing a total of 0-100 bp downstream of the 5' splice site) for three groups of introns.

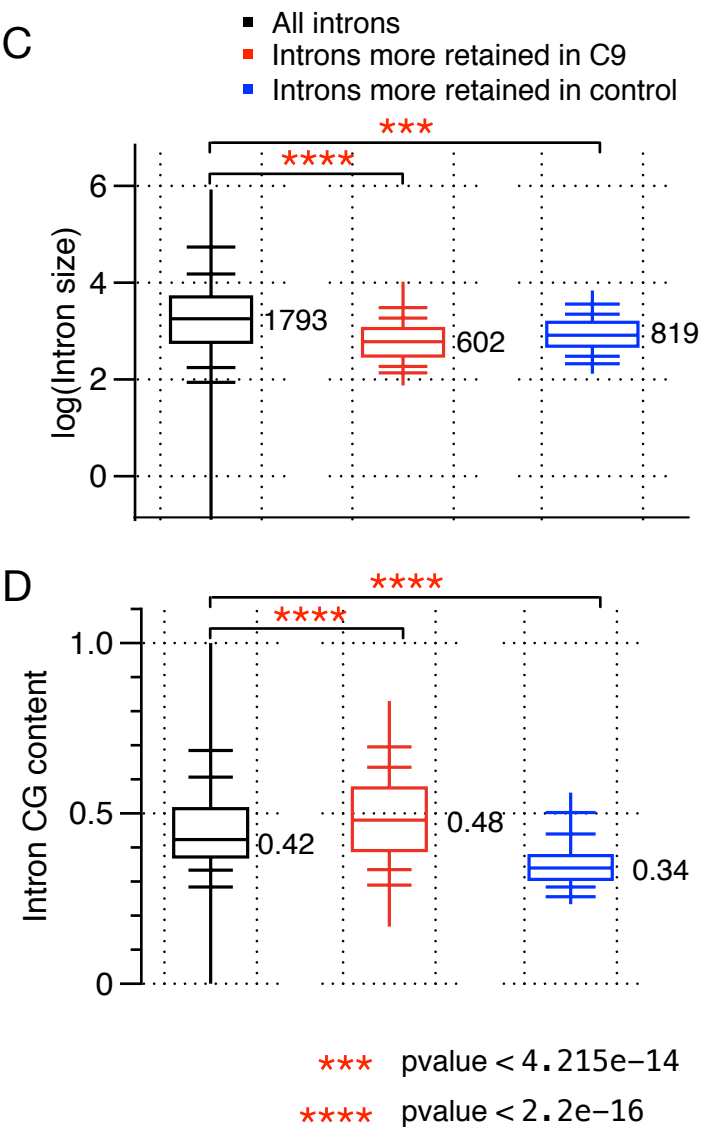
Table 1. Patient sample information.

Table 2. Summary of elevated intron retention events in C9high patient samples compared to normal controls that affect transcripts encoding subunits of the proteasome machinery.

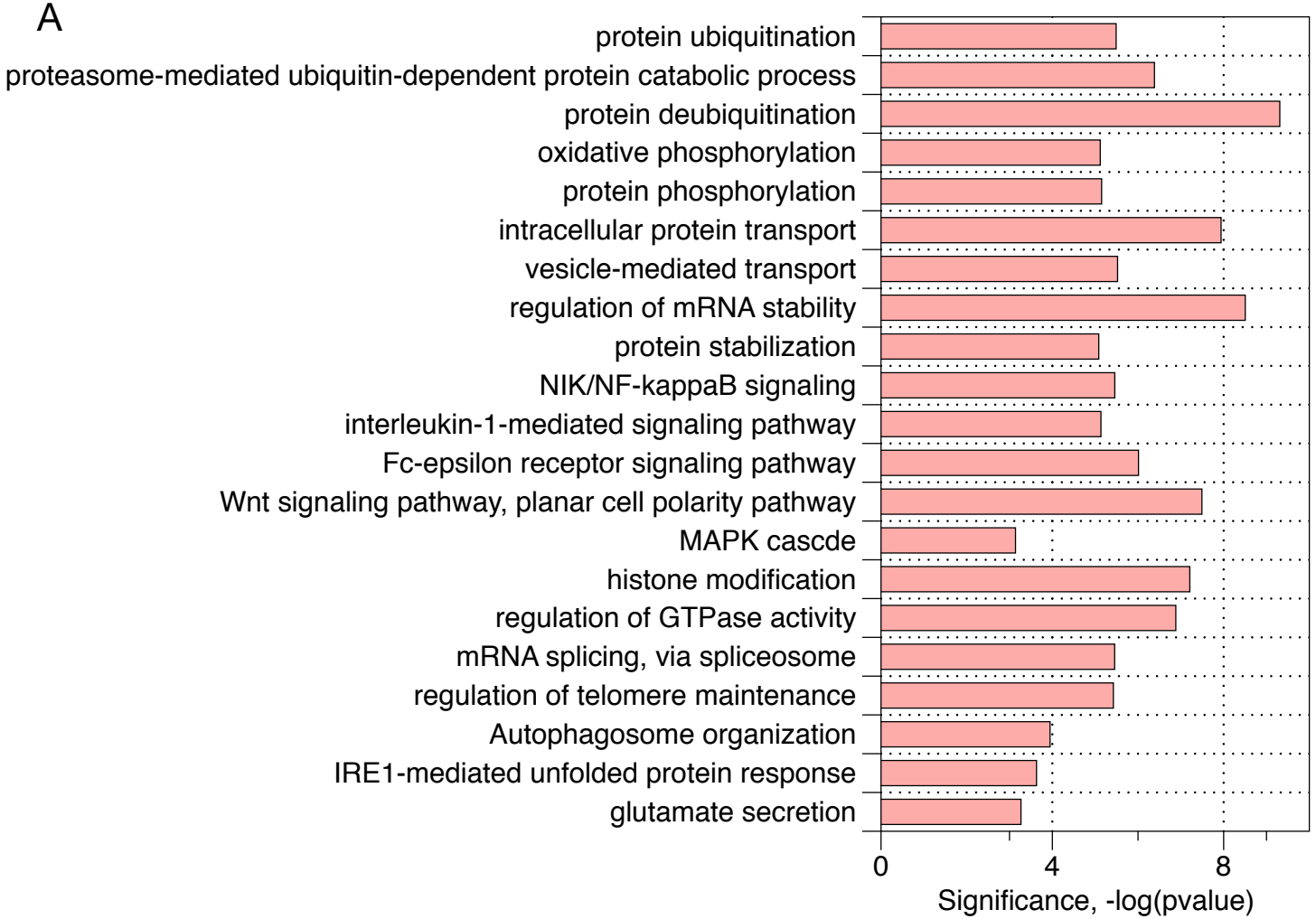

A
Cassette exon
IR
A5SS
A3SS
MXE
Composite
506
3177
266
255
3
474
C9 High Insoluble
vs normal controls
Cassette exon
IR
A5SS
A3SS
MXE
Composite
0
2
0
1
0
1
C9 Low insoluble
v.s. normal controls
1000
2000
3000
# of significantly changed AS events
B
More retained in C9
More retained in WT
2,986
191
-log(qvalue)
ΔΨ, IR (Control - C9 High insoluble)
Significantly changed IR event
C
More retained in C9
More retained in WT
-log(qvalue)
ΔΨ, IR (Control - C9 Low insoluble)
Significantly changed IR event
D
E
CTRL1
CTRL2
CTRL3
C9 High Inso 1
C9 High Inso 2
C9 High Inso 3
388
345
482
257
228
229
112
77
147
33
25
50
hnRNPH1
PSMA3


A
Normal controls
C9 High Insoluble
ΔΨ
0.8
0.4
0
Introns more retained in normal controls
Introns more retained in C9 High Insoluble
non6
non9
non10
non11
non 12
non 13
C91
C93
C910
C95
C98
C911

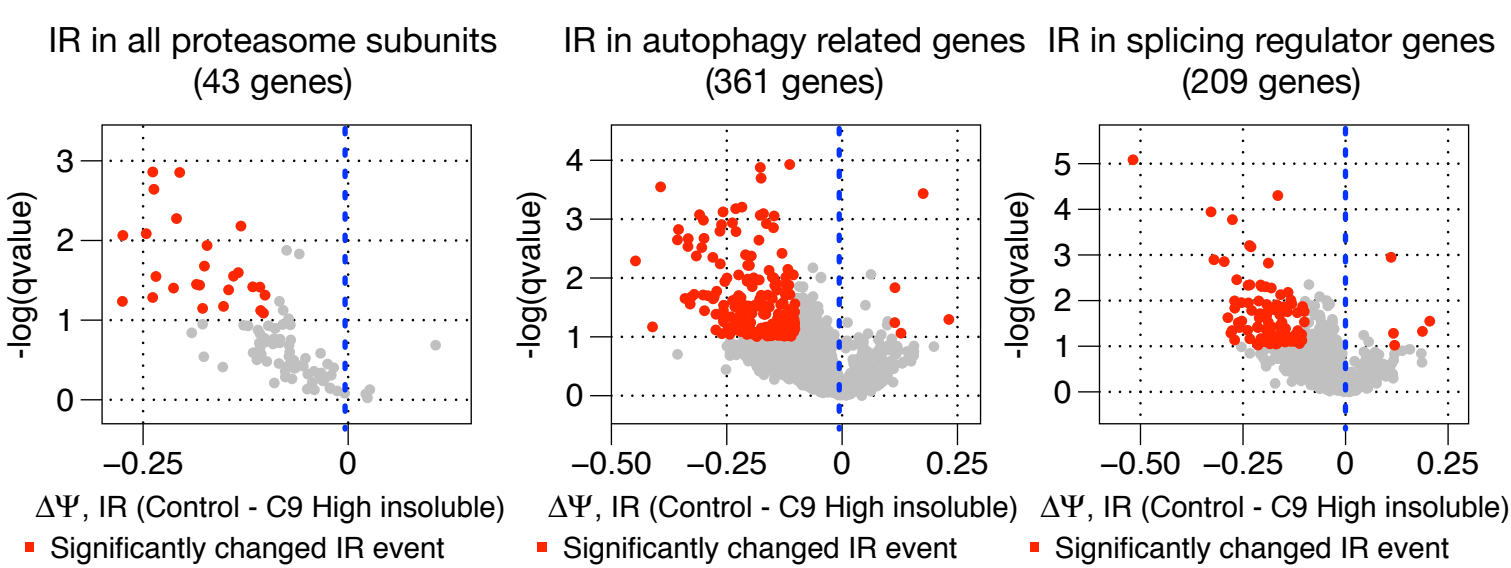

B
Genes with introns more retained in C9 High insoluble
Expression level change
Significant: 15
Not Significant: 1,929
-log(qvalue)
gene expression level fold change
(WT - C9 High Insoluble)

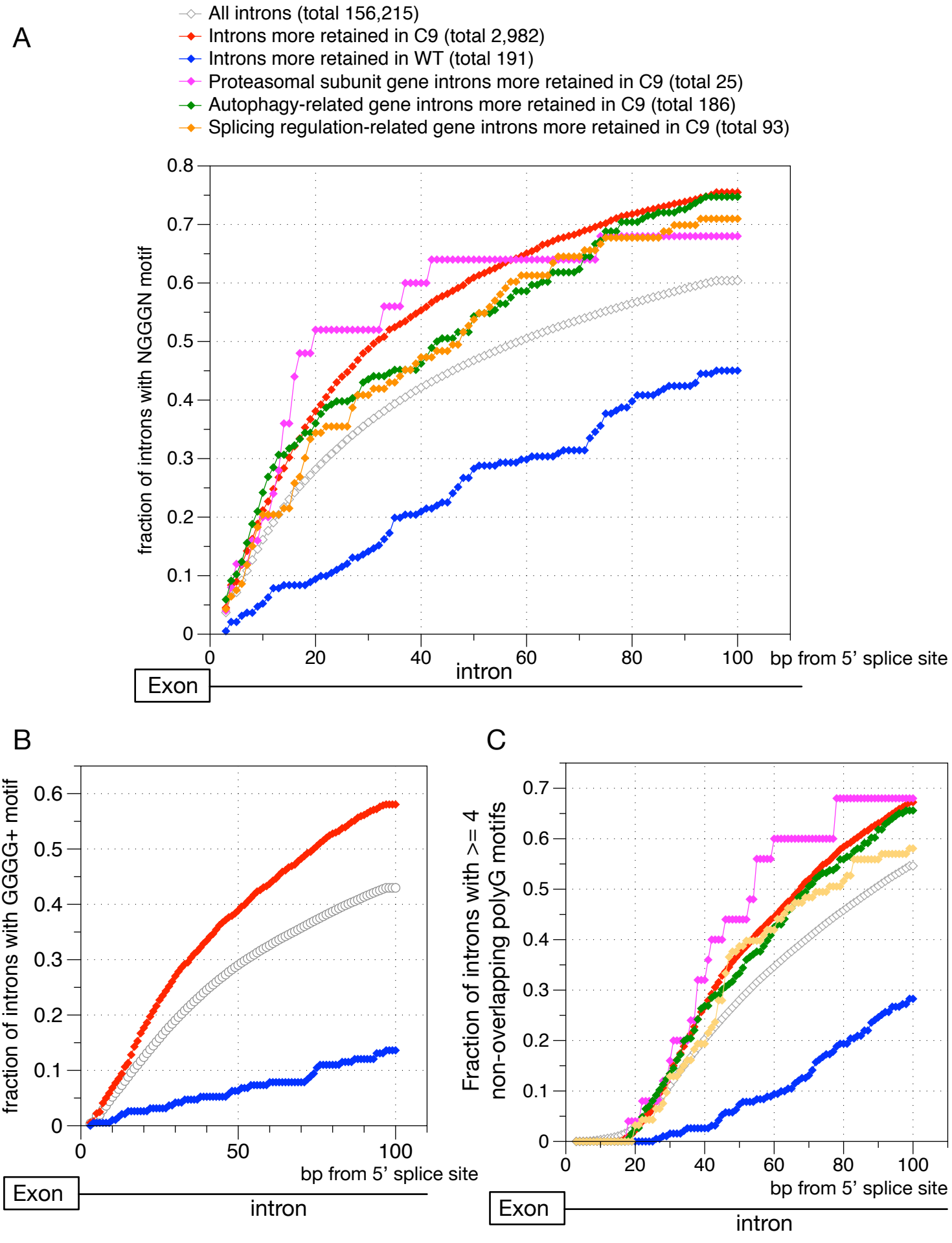

C
All introns
Introns more retained in C9
Introns more retained in control
log(Intron size)
1793
602
819
D
Intron CG content
0.42
0.48
0.34
*** pvalue < 4.215e−14
**** pvalue < 2.2e−16

A


protein ubiquitination
proteasome-mediated ubiquitin-dependent protein catabolic process
protein deubiquitination
oxidative phosphorylation
protein phosphorylation
intracellular protein transport
vesicle-mediated transport
regulation of mRNA stability
protein stabilization
NIK/NF-kappaB signaling
interleukin-1-mediated signaling pathway
Fc-epsilon receptor signaling pathway
Wnt signaling pathway, planar cell polarity pathway
MAPK cascde
histone modification
regulation of GTPase activity
mRNA splicing, via spliceosome
regulation of telomere maintenance
Autophagosome organization
IRE1-mediated unfolded protein response
glutamate secretion
0
4
8
Significance, -log(pvalue)

B


IR in all proteasome subunits
(43 genes)
IR in autophagy related genes
(361 genes)
IR in splicing regulator genes
(209 genes)
-log(qvalue)
ΔΨ, IR (Control - C9 High insoluble)
Significantly changed IR event


A
All introns (total 156,215)
Introns more retained in C9 (total 2,982)
Introns more retained in WT (total 191)
Proteasomal subunit gene introns more retained in C9 (total 25)
Autophagy-related gene introns more retained in C9 (total 186)
Splicing regulation-related gene introns more retained in C9 (total 93)
fraction of introns with NGGGN motif
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
bp from 5' splice site
intron
Exon
B
fraction of introns with GGGG+ motif
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
bp from 5' splice site
Exon
intron
C
Fraction of introns with >= 4 non-overlapping polyG motifs
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
bp from 5' splice site
Exon
intron

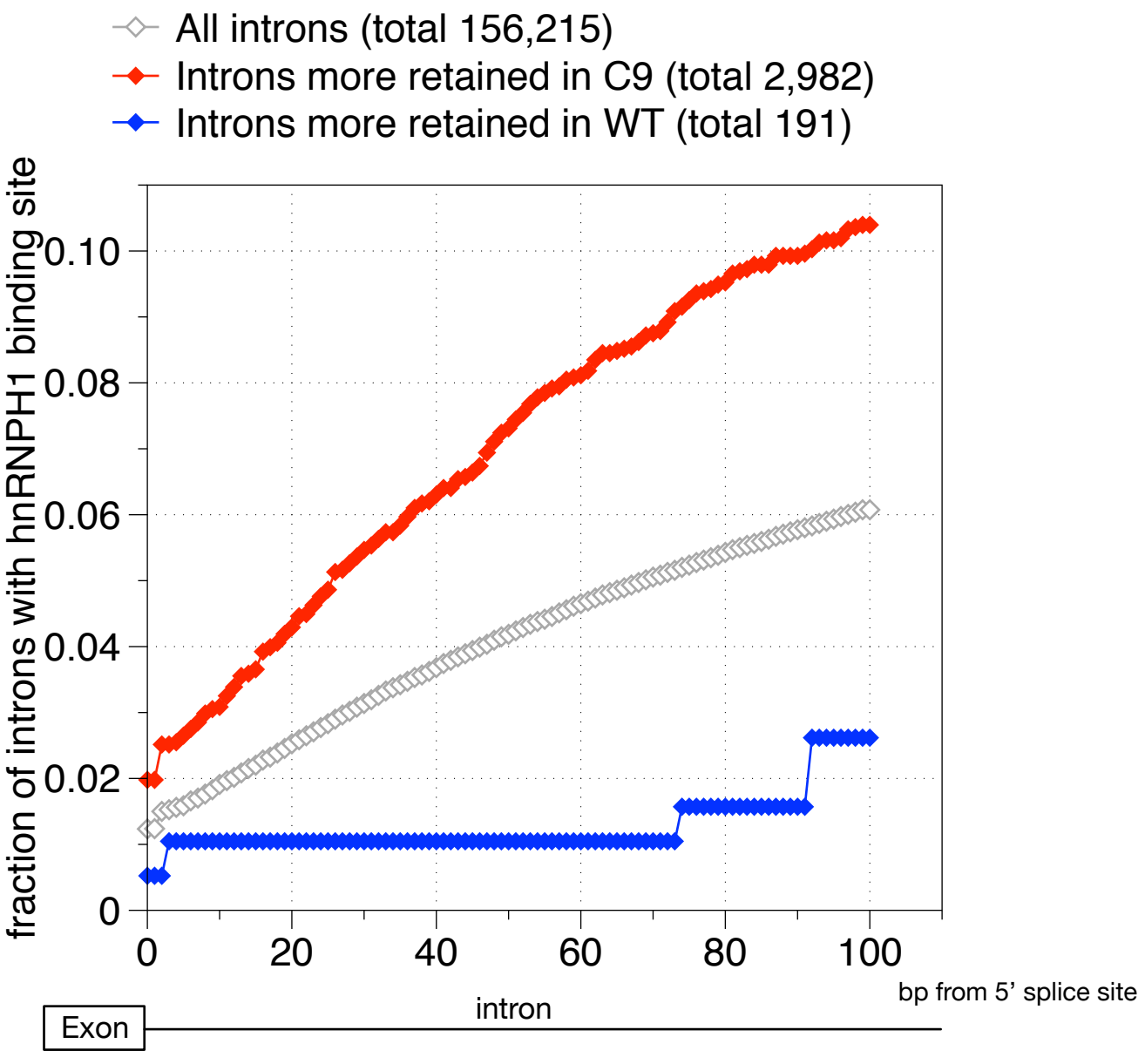

All introns (total 156,215)
Introns more retained in C9 (total 2,982)
Introns more retained in WT (total 191)
fraction of introns with hnRNPH1 binding site
0.10
0.08
0.06
0.04
0.02
0
0
20
40
60
80
100
bp from 5' splice site
intron
Exon

Table 1. Patient sample information.

Sample	RNA-seq ID	Sex	Clinical diagnosis	Age at death	Disease duration	% Insoluble hnRNP H	Group
C91	CGND_HRA_00714	F	ALS	64	1-1.5 years	87.2	C9high
C92	CGND_HRA_00728	F	ALS	64	0.5 years	56	C9low
C93	CGND_HRA_00715	F	ALS	58	1-1.5 years	94.7	C9high
C94	CGND_HRA_00730	M	ALS-FTD	60	0.5-1 years	41.3	C9low
C95	CGND_HRA_00729	F	ALS	65	7-7.5 years	89.2	C9high
C96	CGND_HRA_00716	M	ALS	73	4.5 years	37.2	C9low
C98	CGND_HRA_00726	M	ALS	59	1 year	81.8	C9high
C99	CGND_HRA_00718	M	ALS	70	<2 years	15.8	C9low
C910	CGND_HRA_00453	F	FTD	75	9 years	95.3	C9high
C911	CGND_HRA_00719	M	ALS-FTD	73	2 years	89.5	C9high
C912	CGND_HRA_00720	F	ALS	57	1 year	33.2	C9low
C913	CGND_HRA_00713	F	ALS-FTD	68	6 years	27	C9low
C916	CGND_HRA_00707	F	ALS-FTD	68	6 years	40.3	C9low
non6	CGND_HRA_00206	F	Non-neurological control	54	n/a	n/a	control
non9	CGND_HRA_00721	F	Non-neurological control	90+	n/a	n/a	control
non10	CGND_HRA_00077	F	Non-neurological control	90+	n/a	n/a	control
non11	CGND_HRA_00197	F	Non-neurological control	70	n/a	n/a	control
non12	CGND_HRA_00196	F	Non-neurological control	52	n/a	n/a	control
non13	CGND_HRA_00753	M	Non-neurological control	89	n/a	n/a	control

Gene	Basic molecular function	# of IR events	Effect from IR
PSMA3	Proteasome (prosoma, macropain) subunit, alpha type, 3	3	IR 1: C terminus truncation IR 2: C terminus truncation and change IR 3: C terminus change
PSMA4	Proteasome (prosoma, macropain) subunit, alpha type, 4	2	IR 1: Complete coding protein change IR 2: Complete coding protein change
PSMA7	Proteasome (prosoma, macropain) subunit, alpha type, 7	1	IR: C terminus truncation
PSMB4	Proteasome (prosoma, macropain) subunit, beta type, 4	2	IR 1: C terminus truncation and change IR 2: C terminus truncation
PSMB10	Proteasome (prosoma, macropain) subunit, beta type, 10	1	IR: C terminus truncation and change
PSMC3	Proteasome (prosoma, macropain) 26s subunit, atpase type, 3	1	IR: C terminus change
PSMC4	Proteasome (prosoma, macropain) 26s subunit, atpase type, 4	1	IR: C terminus truncation and change
PSMC5	Proteasome (prosoma, macropain) 26s subunit, alpha type, 5	2	IR 1: C terminus truncation and change IR 2: C terminus truncation
PSMC6	Proteasome (prosoma, macropain) 26s subunit, alpha type, 6	1	IR: C terminus truncation and change
PSMD3	Proteasome (prosoma, macropain) 26s subunit, non-atpase, 3	1	IR: C terminus truncation and change
PSMD6	Proteasome (prosoma, macropain) 26s subunit, non-atpase, 6	1	IR: C terminus truncation and change
PSMD7	Proteasome (prosoma, macropain) 26s subunit, non-atpase, 7	1	IR: C terminus truncation and change
PSMD11	Proteasome (prosoma, macropain) 26s subunit, non-atpase, 11	2	IR 1: C terminus truncation and change IR 2: C terminus truncation and change
PSMD13	Proteasome (prosoma, macropain) 26s subunit, non-atpase, 13	1	IR: C terminus truncation
PSME1	Proteasome (prosoma, macropain) activator subunit 1 (pa28 alpha)	1	IR: C terminus truncation and change
PSME2	Proteasome (prosoma, macropain) activator subunit 2 (pa28 beta)	3	IR 1: C terminus truncation and change IR 2: C terminus truncation and change IR 3: C terminus truncation and change
PSME4	Proteasome (prosoma, macropain) activator subunit 4	1	IR: C terminus truncation and change

Widespread intron retention impairs protein homeostasis in C9orf72 ALS brains

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