









Review

UNC13A in amyotrophic lateral sclerosis: from genetic association to therapeutic target

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ABSTRACT

Amyotrophic lateral sclerosis (ALS) is a fatal neurodegenerative disease with limited treatment options and an incompletely understood pathophysiology. Although genome-wide association studies (GWAS) have advanced our understanding of the disease, the precise manner in which risk polymorphisms contribute to disease pathogenesis remains unclear. Of relevance, GWAS have shown that a polymorphism (rs12608932) in the *UNC13A* gene is associated with risk for both ALS and frontotemporal dementia (FTD). Homozygosity for the C-allele at rs12608932 modifies the ALS phenotype, as these patients are more likely to have bulbar-onset disease, cognitive impairment and FTD at baseline as well as shorter survival. *UNC13A* is expressed in neuronal tissue and is involved in maintaining synaptic active zones, by enabling the priming and docking of synaptic vesicles. In the absence of functional TDP-43, risk variants in *UNC13A* lead to the inclusion of a cryptic exon in *UNC13A* messenger RNA, subsequently leading to nonsense mediated decay, with loss of functional protein. Depletion of *UNC13A* leads to impaired neurotransmission. Recent discoveries have identified *UNC13A* as a potential target for therapy development in ALS, with a confirmatory trial with lithium carbonate in *UNC13A* cases now underway and future approaches with antisense oligonucleotides currently under consideration. Considering *UNC13A* is a potent phenotypic modifier, it may also impact clinical trial outcomes. This present review describes the path from the initial discovery of *UNC13A* as a risk gene in ALS to the current therapeutic options being explored and how knowledge of its distinct phenotype needs to be taken into account in future trials.

INTRODUCTION

Amyotrophic lateral sclerosis (ALS) is a neurodegenerative disorder predominantly characterised by the loss of upper and lower motor neurons.¹ Clinically, the loss of motor neurons results in weakness and spasticity, leading to progressive and severe disability over the course of months to years, and eventually death as a result of respiratory failure.² The lifetime risk of developing ALS for women is 1:400 and is slightly higher for men at 1:350. With riluzole, Edaravone, Nuedexta and Albrioza, several drugs have now been approved for the treatment of ALS, but they have at best a limited effect

on disease progression.^{3–6} As such, the prognosis of ALS remains poor, with a median survival of 3 to 4 years.

Over the past two decades, it has become evident that there is a broad clinical spectrum associated with ALS with multiple subtypes and extensive phenotypic heterogeneity.⁷ For instance, the average age of onset extends from the late teens to well over the age of 90. The initial presenting symptoms also vary greatly between patients and range from a foot drop to dysarthria. Cognitive and behavioural changes are present in up to 50% of patients and nearly 15% of individuals fulfil the criteria for frontotemporal dementia (FTD).^{1,8} Finally, survival is also highly variable and can be as short as a few months in some cases and well over 10 years in others.

This clinical heterogeneity may be in part attributed to the different subtypes of ALS. The disease may be genetic (familial ALS, FALS) or be (apparently) sporadic (SALS). FALS constitutes up to 10% of all cases and generally follows an autosomal dominant pattern of inheritance.⁹ Repeat expansions in the *C9orf72* gene are the most common cause of FALS ($\pm 40\%$), followed by point mutations in *SOD1*, *TARBDP* and *FUS*. Mutations in these genes are also seen in about 10% of apparently sporadic cases. Classically, consensus was that the disease was caused by genetic risk factors in combination with environmental exposures, which together trigger disease.^{9,10} Despite large-scale epidemiological studies, robust environmental factors conferring a large risk of disease have not been identified. Putative risk factors include smoking, repeated head injury and physical activity.¹¹ Currently, the classical distinction between familial and sporadic ALS seems artificial and genetic factors contribute considerably to SALS. Twin and family-based studies show that the genetic basis for the risk of developing SALS is estimated to be approximately 50%.¹² Indeed, genome-wide association studies (GWAS) in sporadic ALS have successfully identified multiple risk loci, including *UNC13A*.¹³

At a cellular level, the mislocalisation and cytoplasmic aggregation of hyperphosphorylated and ubiquitinated TAR DNA-binding protein 43 (TDP-43) is a pathological hallmark of ALS that is seen in 98% of all cases.¹⁴ TDP-43 appears to



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cause neurotoxicity through both dysregulation of nuclear RNA processing as well as cytoplasmic TDP-43 aggregation, which causes a series of aberrant processes including cellular stress, aberrant stress granule formation, mitochondrial dysfunction, altered translation, reduced autophagy and proteosomal dysfunction.¹⁵ More recently, the molecular mechanisms by which genetic variation in the *UNC13A* gene confers risk and modifies the ALS phenotype have been linked to TDP-43 pathology.^{16 17}

This current review describes the path from the initial discovery of *UNC13A* as a risk gene and its effect on the ALS phenotype through to the understanding of its molecular action and yet-to-come elucidation of its pathophysiological impact and potential as a therapeutic target. The strategies and challenges associated with developing a targeted treatment for the *UNC13A* subgroup of ALS patients will likely also apply to other subgroups. As our understanding of the genetics of ALS grows, the lessons learnt here are likely to be more broadly applicable.

GENETIC ASSOCIATION STUDIES IN ALS

Genetic research in ALS, as well as in other fields, was initially focused on the identification of pathogenic mutations through classical linkage in ALS pedigrees in which there was a clear Mendelian pattern of inheritance. Using this approach, the first FALS gene (superoxidase dismutase 1, *SOD1*) was discovered in 1993,¹⁸ which led the subsequent discovery of major ALS genes like *TARDBP* and Fused In Sarcoma (*FUS*)/*TLS*. Given the large genetic contribution to SALS, researchers also started to look for genetic risk factors in sporadic cases through candidate gene approaches which were based on existing knowledge of gene/protein function and pathophysiology. Although state-of-the-art at the time, candidate gene approaches were inherently vulnerable to bias and did not significantly further our understanding of ALS. It was not until the introduction of large-scale, high-throughput genotyping techniques that ALS genetics progressed.¹⁹

Initially, this was through GWAS that allow the screening of common genetic variation in large populations. GWAS makes use of high throughput genotyping and linkage disequilibrium (LD) to screen the genome for common variants (single-nucleotide polymorphisms, SNPs) associated with the trait of interest.²⁰ GWAS were first applied in ALS in 2007 with initially varying success to identify new risk loci.²¹ Over time, GWAS methodology improved, and increasing sample size allowed the interrogation of both common (>1%) and rare (<1%) variants, which led to the identification of robust and replicable genetic risk factors.¹³ Importantly, GWAS identified the chromosome 9p21.2 locus that was already shown to be linked to familial ALS and 2 years later found to harbour the *C9orf72* repeat expansion.^{22–25}

The latest and largest GWAS, to date, with 29 612 cases and 122 656 controls, identified 15 risk loci, 7 of which had not been previously described.¹³ Through the use of novel sequencing techniques, over 60 different genes have been identified for ALS and combined have demonstrated a monogenetic basis in $\pm 70\%$ of FALS cases and in 10% of SALS.^{19 21} Genetic mutations which are known to be monogenetic are also detected through GWAS.¹³ The depths of the human genome combined with the aforementioned developments in the genetic research of ALS lead to believe that more different genetic risk factors and more certainty about their role in the pathophysiology will be discovered in the future.

Despite the contribution of GWAS to our knowledge of ALS, translating these ALS risk SNPs into disease models has been

challenging. SNPs serve as markers to highlight a genetic locus, leaving the true causal mutation unknown.²⁶ The SNPs found by GWAS typically convey a limited effect on disease risk compared with classical Mendelian genes, which is reflected by small ORs (typically <1.5).^{26 27} The SNP at rs12608932 in *UNC13A* was one of the first and most robust ALS-associated loci to be identified through GWAS (figure 1A,B). In the latest GWAS, it has an OR of 1.12 and modestly increases the risk for ALS from 1 in 350 to 1.12 in 350.^{1 13} Interestingly, early studies found strong effects of this SNP on survival, which prompted further interrogation of *UNC13A* as a phenotypic modifier.²⁸

UNC13A-ALS: A DISTINCT PHENOTYPE

The association between rs12608932 (located in *UNC13A*) and ALS was first described in 2009.²³ Since then, this association has been replicated repeatedly in larger GWAS cohorts of patients with ALS of European ancestries.^{13 28–31} Another SNP in *UNC13A*, rs12973192, was found to be associated with ALS in 2018.³² This SNP is in high LD with rs12608932 only in European populations and seems to have an additive pathophysiological effect.^{17 33} This finding might explain the less robust association for both SNPs with ALS in South-East Asian populations.^{13 34–36}

Homozygosity for the C-allele at rs12608932 was found to lead to a shorter survival when compared with homozygous (A/A) or heterozygous individuals (A/C), with a decrease in median survival reported ranging from 5 months to 1 year.^{13 28 30 37 38} This is seen in figure 2 under a recessive model. Survival under an additive model and adjusted survival curves are found in online supplemental material. Associations between homozygosity for the C-allele at rs12608932 and age of onset are less robust, with one study finding a higher median age of onset (65.5 vs 63.5 for A/A homozygosity).³⁷ Other research found no significant relation for *UNC13A* and age of onset.^{13 30}

Patients homozygous for the C-allele at SNP rs12608932 were more likely to have a bulbar onset of symptoms (43.1% vs 30.6%) and a lower functional vital capacity at baseline (86.5% vs 90.1%).³⁷ Furthermore, behavioural disinhibition (13.2% vs 7.1%) and cognitive deficits were more frequent and there was a marked thinning in several frontal and temporal cortical regions.^{37 39} Pathological examination of the middle frontal, temporal and motor cortices of patients with ALS homozygous for the C-allele at rs12608932 were found to have strongly increased burden of TDP-43 compared with AA-homozygous patients, indicating that these individuals were more severely affected.³⁹ An overview of clinical characteristics of *UNC13A* C/C homozygosity is found in figure 3.

UNC13A AS A COMMON RISK FACTOR FOR ALS AND FTD WITH TDP-43 PATHOLOGY

ALS forms a disease spectrum with FTD, with clinical phenotypes displaying characteristics of both disease.^{1 8} FTD is a progressive dementia characterised by either behavioural disinhibition or several different types of aphasia and has a yearly incidence of 15 to 22 per 100,000.^{15 40} Pathologically, FTD is characterised by clustering of either TDP-43, which is most common with $\sim 50\%$ of cases, Tau or FUS, which all three are associated with different phenotypes.¹⁴ The relation for ALS and FTD specifically concerns FTD with TDP-43 inclusions (FTD-TDP).⁴¹

Approximately 10%–15% of all patients with ALS meet criteria for FTD at baseline, and inversely, 15% of patients with FTD develop motor neuron symptoms over the course of the disease.^{1 8} Presence of FTD in patients with ALS is associated

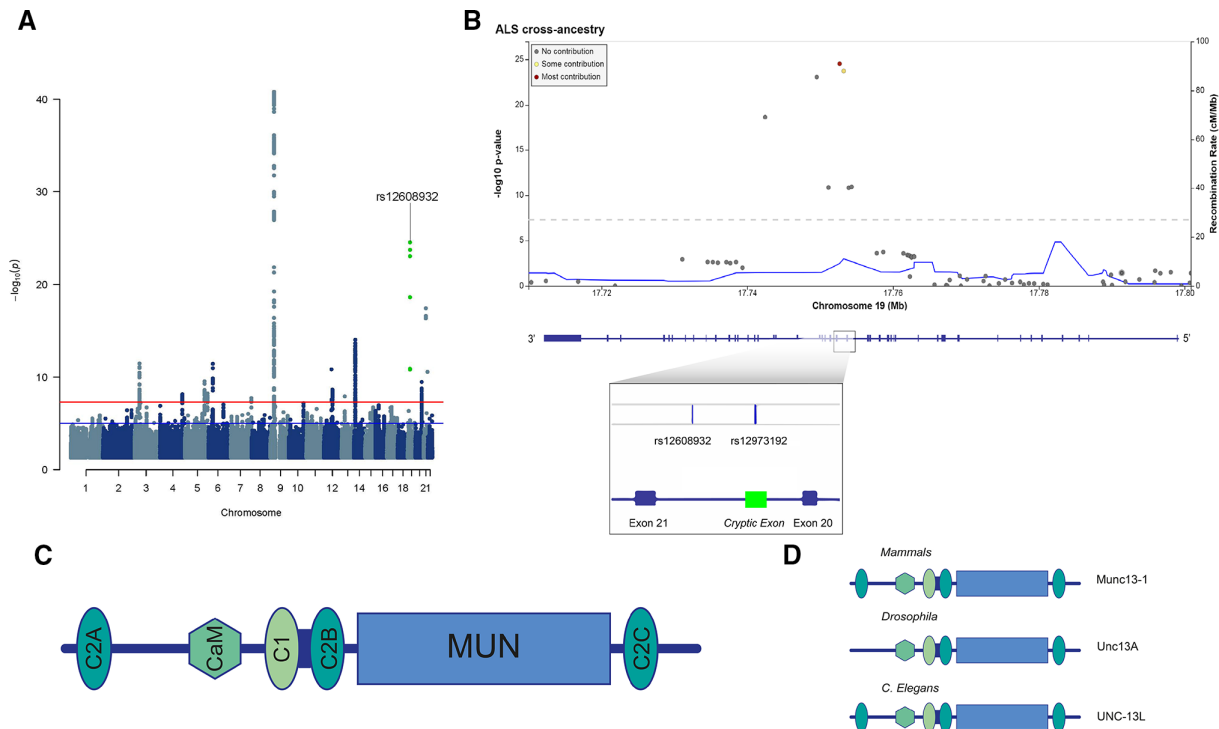


Figure 1 Manhattan plot and fine locus mapping describing the location of risk SNPs in the genetic structure of *UNC13A*. (A) shows a Manhattan plot of cross-ancestry data available through Project MinE, showing the relation of SNP hits at different chromosome locations (x-axis) with a corresponding $-\log_{10}(p)$ value (y-axis). The red line (5.0×10^{-8}) indicates the threshold for genome wide significance. Significant SNP hits on chromosome 19 are highlighted in green, with the top variant (rs12608930) annotated. (B) shows SNP locations on the *UNC13A* gene on chromosome 19 (x-axis) with their significance in relation to ALS (y-axis), derived from data available through project Mine. rs12608932 is indicated by a red dot, rs12973192 is indicated by a yellow dot. The genetic intronic/exonic structure of *UNC13A* is depicted, read from 5' to 3'. The detailed graph depicts the location of risk SNPs in relation to the cryptic exon. Parts of the image were adapted from Locuszoom.¹⁰¹ (C) shows a schematic representation of the canonical *UNC13A* protein with associated domains.⁶⁷ The CaM domain is the Calmodulin binding domain. (D) shows the evolutionary stability through different species. The core of the *UNC13* protein is conserved both through different species as well as in different subforms.⁶⁷ ALS, amyotrophic lateral sclerosis; SNP, single-nucleotide polymorphism.

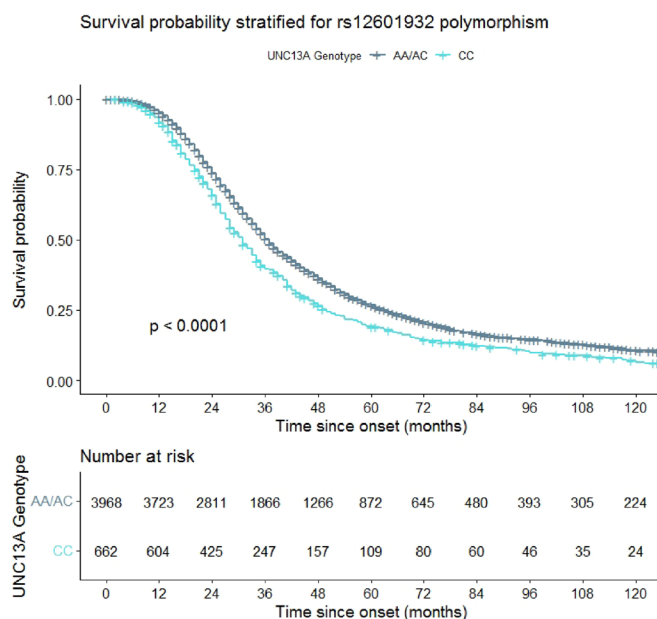


Figure 2 Overall survival for rs12608932 polymorphism. The p-value indicates the difference in cumulative risk between homozygous C-allele carriers versus non-carriers under a recessive model. Based on data from Van Rheenen *et al.*¹³

with a worse survival.⁴² The C-allele at rs12608932 was found to convey risk for both ALS and FTD-TDP.⁴³ Later findings confirmed that *UNC13A* is part of a shared genetic basis for both diseases, among other genes such as *C9orf72*.^{13 44} Patients with ALS homozygous for the C-allele at rs12608932 in *UNC13A* were found to have an increased risk of FTD at baseline, independent of age at onset.³⁷ Inversely, rs12608932 in *UNC13A* was found to confer risk of TDP-43-associated FTD, both with and without motor neuron symptoms.^{41 44} A specific association was found for subtype B of FTD-TDP, and rs12973192 in *UNC13A*, which is in LD with rs12608932.⁴¹ Type B FTD-TDP is pathologically characterised by round TDP-43 inclusions throughout the depths of cortical layers and is clinically associated with both behavioural FTD and FTD with motor neuron symptoms; patients with type B FTD-TDP have a markedly shorter survival than other subtypes.⁴¹

STRUCTURE AND FUNCTION OF *UNC13A*

UNC13 was first described in the worm species *Caenorhabditis Elegans*, named as such because mutant worms were grouped based on their movement phenotypes. Defects in this gene were associated with 'uncoordinated' movement and paralysis.⁴⁵ In 1995, the Mammalian *UNC13* (Munc-13) protein group was discovered in the central nervous system of rats, of which Munc13-1 was most ubiquitous.⁴⁶ Munc13-1 is a large protein with a molecular weight around 200 kDa, containing several binding domains with different functions at its C-terminal and

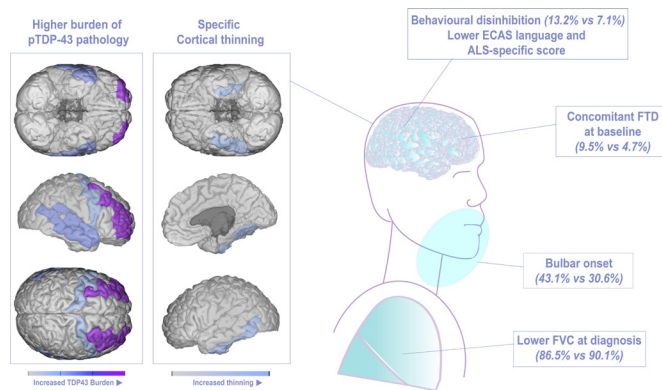


Figure 3 Overview of the clinical phenotype of ALS patients conveyed by rs12608932. The left frame depicts brain regions with increased pTDP-43 burden in patients with C/C genotype in rs12608932 when compared to A/A: middle frontal cortex (8.26 times higher), temporal cortex (4.40 times higher) and motor cortex (3.04 times higher).³⁹ The right frame depicts regions with increased cortical thinning associated with homozygosity for the C-allele at rs12608932, found through magnetic resonance imaging: the right fusiform cortex and the left inferior temporal cortex.³⁷ The right part depicts clinical characteristics more likely to be present in patients homozygosity for the C-allele at rs12608932.³⁷ Percentages are compared to the AA/AC. Brain images were adapted using Brainpainter.¹⁰¹ ALS, amyotrophic lateral sclerosis; ECAS, Edinburgh Cognitive and Behavioural ALS Screen, FTD, frontotemporal dementia, FVC, forced vital capacity, pTDP-43, phosphorylated 43kDa TAR DNA-binding protein.

N-terminal parts, and is exclusively found in presynaptic terminals of the nervous system.^{46,47} UNC13A is the human orthologue of Munc13-1, and these proteins were found to be evolutionary stable, meaning that their structure and function are similar across species. A schematic representation of UNC13A and its conservation through species are seen in figure 1C,D. UNC13A is important for facilitating several crucial steps in neurotransmission, enabling sustained neurotransmission and maintaining and constructing the sites where neurotransmission can take place in so called 'active zones'.⁴⁸

Neurotransmitters are collected and placed into synaptic vesicles (SVs) by the Golgi apparatus which then, through mediation of UNC13A, collect at the active zone in the presynaptic membrane.^{49,50} Here, SVs undergo a series of processes mediated by UNC13A, which make SV fusion competent. First, UNC13A is recruited by Rab3-interacting molecule (RIM) proteins, which activate UNC13A and bind calcium channels to recruit them to the docking site.⁵¹ The C1/C₂B domain of UNC13A, together with UNC18, mediates the further stages of docking by assembling soluble N-ethylmaleimide-sensitive factor attachment receptor (SNARE)-complexes, a collection of water soluble bridging molecules consisting of synaptobrevin, SNAP-25, which connect to the SVs, and syntaxin-1, which connects to the presynaptic membrane.^{48,52-54} UNC13A interacts independently of UNC18 with syntaxin-1 and induces a structural transition to a functional open state; through this, UNC13A mediates the assembly of SNARE complexes and binds a total of 6 SNAREs to each SV.^{48,52,53,55,56} Through undergoing several structural transitions,⁵⁷ UNC13A is involved in sequential steps of SV priming. Priming by UNC13A C1-domain activation decreases the energy needed to fuse to the cell membrane, makes SV ready to fuse and makes it possible for all the collected SVs to fuse at the same time.^{58,59} The final step of neurotransmitter release is the fusion of the vesicles itself triggered by the influx of Ca²⁺, after which

neurotransmitters are released into the synapse where they bind to the corresponding receptors and are eventually recycled.^{59,60} UNC13A limits the site where neurotransmission can take place by initiating and maintaining synaptic active zones.⁶¹ UNC13A inhibits axonal growth both in vitro and in vivo in mice⁶² and triggers axonal branching, suggesting expression of UNC13A is typical for fully grown neurons and makes it possible for connections with nearby cells to be formed.

Several domains of the UNC13A protein are involved in synaptic plasticity,^{51,63} the ability of neurons to change their connections based on activity either over short periods of time, which is involved in processes such as motor control, and longer periods, involved in learning and memory. Heterodimerisation of the C2A domain of UNC13A with RIM,^{64,65} which recruits Ca²⁺-channels in the active zones, is important for docking and priming. In order to effectuate short-term plasticity, SVs are recruited into readily releasable pools (RRPs), which are stand-by in the presynaptic terminal in order to effectuate rapidly fuse when needed, for which the DAG-binding C1 domain of UNC13A plays a crucial role.⁶³ UNC13A and UNC18 interact with the SNARE complex in order to prevent NSF/SNAPa depriming,^{66,67} which keeps the RRP fusion competent. The calmodulin binding domain is involved in activity-dependent RRP refilling,⁶⁸ which is attenuated to residual Ca²⁺, shaping short-term plasticity during sustained neurotransmission. Finally, the C₂B-domain of UNC13A regulated the recovery from high frequency stimulation through interaction with voltage-gated calcium channels,^{69,70} further enabling short-term plasticity.

PATHOPHYSIOLOGICAL MECHANISMS IN UNC13A

Mutations in UNC13A have also been reported in other diseases. A homozygous nonsense loss of function mutation in the N-terminal of UNC13A was identified in a patient with severe hypotonia, cortical hyperexcitability and fatal myasthenia.⁷¹ In vitro analysis of cultured muscle cells of this patient showed end plate potentials which were 2% of normal, indicating a severe decrease in neurotransmission. These clinical signs were thought to be the result of a loss of functional syntaxin-1B, which was left in a non-operational state due to the loss of UNC13A.⁷² A gain of function mutation in UNC13A was shown to have opposite effects⁷²; a Pro814Leu exchange was found to lead to a dyskinesic movement disorder caused by an increase in the probability of SV release. This gain of function mutation was induced in neuronal cultures and was shown to increase synaptic strength of hippocampal and striatal neurons of mouse models and cholinergic neurons in neuromuscular junctions due to a higher SV release rate.

Based on the known variation in UNC13A,³³ genetic mutations leading to nonsense mutations or mutations leading to loss of function are much more rare than is to be expected based on chance. As such, UNC13A is a very constrained gene, which could lead to believe that mutations leading to an alteration or loss of its function is more often than not inviable. Importantly, the UNC13A SNPs associated with ALS are intronic and do not lead to changes in translation of the main UNC13A transcripts.¹⁷ Indeed, although rs12608932 and rs12973192 are associated with ALS, they also occur at a high frequency in healthy individuals,¹³ and around 10% of the European population is homozygous without pathophysiological consequences. This makes their role in ALS pathogenesis more elusive and questioning whether they had a direct effect or were merely tagging other yet-to-be identified changes.

Cryptic exon inclusion secondary to TDP-43 mislocalisation

Cryptic exons have recently been identified as the basis of *UNC13A* ALS pathophysiology.^{16 17} The process of splicing is regulated by TDP-43,^{14 73 74} a widely expressed protein which plays a role in RNA processing and transport. Specifically, one of TDP-43's functions is that of binding to intronic sequences and repressing the inclusion of certain segments into mature RNA. On TDP-43 depletion, this repression is lost and normally intronic sequences, called cryptic exons, are included in messenger RNA (mRNA). Cryptic exons often introduce premature stop codons or frameshift mutations,^{16 74} which lead to nonsense-mediated decay of mRNA. In ALS-FTD, TDP-43 cytosolic aggregates are found in up to 98% of sporadic ALS cases and in 60%–83% of FTD pathology,⁷⁵ depending on the clinical phenotype and are often accompanied by a nuclear depletion of TDP-43, leading to the appearance of cryptic exons.^{15 73} The cryptic exon is detected specifically in tissues affected by TDP-43 pathology (motor cortex and spinal cord in ALS patients and frontal and temporal cortices in FTD patients) and is absent in the (although small) percentage of non-TDP-43-related ALS-FTD.¹⁷ The two previously described SNPs (rs12608932(A>C) and rs12973192(C>G)) and a novel third mutation (rs56041637) are located either within the *UNC13A* cryptic exon or the intron it originates from, as is seen in figure 1B. Although on TDP-43 depletion, the cryptic exon appears also in the absence of these variants, their presence was shown to alter the affinity of TDP-43 binding and make the inclusion of cryptic exon in mRNA more likely.^{16 17 23} Therefore, the loss of TDP-43, combined with the presence of these risk variants, leads to a drastic reduction in viable *UNC13A* mRNA and proteins, as can be seen in figure 4A. The above described mechanism linking TDP-43 pathology with *UNC13A* loss explains how risk SNPs can occur frequently in the general population, as they exert their action only when the TDP-43 pathology has started and might also explain in part the effect of the SNPs on disease progression.

Furthermore, TDP-43 pathology seems to affect neurons in a cell-specific manner, indicating that downstream processes, such as *UNC13A* pathology, are also selective to these groups of cells.⁷⁶ Finally, TDP-43 pathology has been found to be associated with impaired synaptic transmission and synaptic loss, but it is as of yet unclear if, or in what manner, this is dependent on loss of *UNC13A*.^{77–80}

Loss in synaptic transmission

As can be expected according to the main function of *UNC13A*, loss of *UNC13A* leads to impairment of neurotransmission (figure 4B). Loss of *UNC13A* leads to less efficient or total absence of evoked neurotransmission, with cells lacking *UNC13A* releasing SVs at a nearly four times slower rate, mainly due to a dramatic decrease in the RRP and a lack in bridging.^{48 50 52 59} *UNC13A* was shown to mediate SV release through activity-dependent Ca^{2+} –phospholipid binding in the C₂B domain; a point mutation induced to abolish Ca^{2+} binding in this domain showed a slower recovery rate of the RRP.⁷⁰ The decrease in RRP recovery increased the latency between stimulus and recovery, leading to believe that Ca^{2+} binding to *UNC13A* is instrumental in fidelity of neurotransmission during maintained firing of action potentials.

In cultivated hippocampal cells, loss of *UNC13A* was shown to mainly affect glutamatergic neurotransmission.^{50 58} GABAergic neurons seem to have an inherently lower threshold for vesicular fusion and are more affected by the loss of all *UNC13* proteins, instead of *UNC13A* specifically.^{58 59} This might

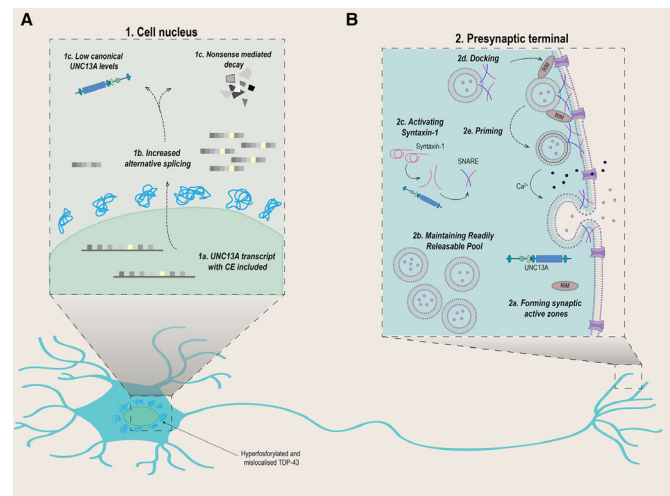


Figure 4 Pathological cryptic exon inclusion and the putative disease mechanisms in *UNC13A*.

1. Cryptic exon inclusion has been found to be the pathological basis in *UNC13A* associated ALS. As a result of mislocalisation of TDP-43 outside of the cell nucleus, transcripts of *UNC13A* (1a) are spliced incorrectly, leading to the inclusion of the cryptic exon in mature *UNC13A* transcripts. This leads to nonsense mediated decay of proteins produced by reading messenger RNA containing the cryptic exon and vastly lower functional protein levels (1c).

2. *UNC13A* has been found to be involved in several processes pertaining to synaptic transmission. *UNC13A* forms and maintains synaptic active zones due, which orchestrates the localisation of several proteins essential to neurotransmission, such as calcium channels, RIM-molecules, synaptobrevin and syntaxin-1 (2a). *UNC13A* maintains the readily releasable pool, a collection of synaptic vesicles able to fuse quickly in order to facilitate neurotransmission (2b). *UNC13A* induces a change in conformation of syntaxin-1 to an open state, which activates it and enables the assembly of SNARE-complexes. *UNC13A* orchestrates the docking of 6 SNARE-complexes to each synaptic vesicle in order for it to tether to the presynaptic membrane. RIM interacts with *UNC13A* and recruits calcium (Ca^{2+}) channels to the docked vesicle (2d). *UNC13A* primes synaptic vesicles in order to lower the Calcium (Ca^{2+}) threshold needed for fusion with the presynaptic membrane (2e). Due to an influx of Ca^{2+} , the synaptic vesicles fuse fully and neurotransmitters are released. A decrease in function of *UNC13A* could lead to a decrease in several or all of the aforementioned processes.

indicate that mutations in *UNC13A* mainly affect excitatory neurotransmission.

Maintaining neuronal health and function

Apart from its role in neurotransmission, loss of *UNC13A* affects neuronal structure and health.^{71 81 82} Absence of *UNC13A* decreased the release of dense core vesicles up to 60%.⁸¹ Dense core vesicles contain neuropeptides, neurotrophic factors and other regulatory substances which develop neurons in the adult brain and are important in the formation of synaptic active zones.⁸³ A downstream effect of the loss in *UNC13A* is a simultaneous loss of syntaxin-1, which is instrumental in both vesicle docking and maintaining neuronal health, as it leads to increased rates of degradation in both developing and adult neuronal cells.^{71 82} Expression levels of both syntaxin-1B, an isoform, and *UNC13A* were lowered in the transcriptome of ventral horns of ALS patients.⁸⁴ Furthermore, there was reduced expression of circulating microRNA related to either *UNC13A* or *UNC18* in

ALS, implicating a loss of neuronal transmission in part in the pathophysiology of ALS.⁸⁵

POTENTIAL TREATMENTS TARGETING *UNC13A*

Lithium carbonate

The application of lithium carbonate in treating ALS has been researched extensively. Initially, the results of a phase two trial showed a very promising effect on survival in patients with ALS when compared with treatment with riluzole alone.⁸⁶ After this initial publication, five randomised controlled trials were conducted with none finding a benefit of lithium carbonate compared with control.^{87–89} A meta-analysis confirmed that there is no benefit of lithium carbonate to the ALS population as a whole.⁹⁰ In post-hoc analyses, it was interrogated whether genetic subgroups (*C9ORF72* and *UNC13A*) responded differently to treatment with lithium carbonate.⁹⁰ Strikingly, patients homozygous for the C/C genotype of rs12608932 allocated to lithium carbonate exhibited a significantly higher 12 month survival probability compared with those in controls arms (69.7% compared with 40.1%, respectively).⁹⁰ Although these data suggested that lithium carbonate might be effective in this genetic subgroup, these represent results will need to be replicated in a confirmatory trial. Therefore, an international, multi-centre, double-blind, placebo-controlled study enrolling patients with ALS with homozygous for the risk SNP rs12608932 has been initiated. The study is being undertaken in 15 ALS centres originating from seven countries in Europe and Australia (EudraCT 2020-000579-19). A total of 171 patients homozygous for the C-allele at rs12608932 will be included. A protocol for this study has recently been published.⁹¹

While the mechanism by which lithium carbonate could influence disease progression in *UNC13A*-ALS remains unclear, pre-clinical studies show that lithium induces sprouting of pyramidal neurons and induces synaptogenesis, which might counter-effect the previously described loss in synaptic transmission resulting from *UNC13A* depletion.^{92–93} Other proposed mechanisms relate to regulation of intracellular calcium homeostasis and an increase in autophagy, a process through which cells are able to degrade intracellular components, which was shown to be activated by lithium.^{93–94} Furthermore, it may also be that the effect of lithium can be detected in the trial context in faster-progressing individuals, which are more likely to be homozygous for the risk SNP.

Other potential therapeutic strategies

Drugs with a similar structure to DNA and RNA, called nucleic acid therapeutics, can be used to specifically target mRNA in order to regulate protein expression.⁹⁵ Single-stranded synthetic antisense oligonucleotides (ASOs) are able to bind the junctions between introns and exons in mRNA in order to regulate splicing and induce exon skipping.⁹⁶ This could be used to inhibit the inclusion of the cryptic exon in *UNC13A* induced by TDP-43 pathology, leading to a rescue of functional protein levels. Splicing modulating therapies are already being used to treat spinal muscular atrophy, which has been a tremendous step forward for these patients, but importantly also demonstrates proof-of-concept.⁹⁷ ASO trials are currently underway for other genetic targets associated with ALS,⁹⁸ such as *SOD1*, *FUS* and *C9ORF72* and *Ataxin-2* repeat expansions.

Of relevance, Bryostatin 1 was discovered to target *UNC13A* in vitro.⁹⁹ Bryostatin 1 is a natural compound isolated from a specific genus of moss animals, which is a diglyceride (DAG) homologue. DAG interacts both with protein kinase C (PKC)

domain as well as the C1-domain of *Munc13-1*, which were both found to have similar structures. Bryostatin 1 induces plasma membrane translocation of *UNC13A* and upregulates *UNC13A* expression. In this manner, it could contribute to maintaining synaptic structure and health, but it is unlikely that these potentially beneficial effects take place when there is no functional protein due to cryptic exon inclusion or that it could be used without side effects due to its simultaneous activation of PKC.¹⁶

Trial design

Knowledge of *UNC13A* should be taken into account when designing clinical trials for the treatment of ALS. Due to the association of *UNC13A* with survival, having an over-representation of patients homozygous for the C-allele at rs12608932 in treatment or control groups could, respectively, decrease the chance of detecting treatment effects or introduce bias; for example, a study of 25 patients, there is a 85% risk of an imbalance of 5% for C/C homozygosity at rs12608932.¹⁰⁰ Similar risks for imbalance in frequency of *C9orf72* repeat expansions apply. These findings seem to warrant incorporating genetics into the design and conduct of clinical trials.^{100–101} Finally, as *UNC13A* is a shared genetic cause for ALS and FTD, compounds that are effective in patients with ALS could also warrant examination in patients with FTD.

CONCLUSION

Here, we have reviewed the association of *UNC13A* with ALS, its effect on survival and the distinct clinical phenotype associated with it. We described how TDP-43 pathology, the hallmark of ALS, leads to the inclusion of a cryptic exon in *UNC13A* and subsequent nonsense-mediated decay lowering functional protein levels, in turn likely affecting neurotransmissions, synaptic plasticity and neuronal health. Finally, we have described possible treatment strategies, in particular, those targeting *UNC13A* sub-populations, such as lithium carbonate and exon skipping ASOs. Clinical, genetic and biological findings all demonstrate that *UNC13A* is a potent phenotypic modifier in ALS, but with a much smaller effect on disease risk. This finding warrants further research on genetic modifiers of ALS phenotypes as further knowledge of these modifiers could guide trial design and therapy development.

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REFERENCES

- van Es MA, Hardiman O, Chio A, et al. Amyotrophic lateral sclerosis. *Lancet* 2017;390:2084–98.
- Kiernan MC, Vucic S, Cheah BC, et al. Amyotrophic lateral sclerosis. *Lancet* 2011;377:942–55.
- Abe K, Aoki M, Tsuboi S, et al. Safety and efficacy of edaravone in well defined patients with amyotrophic lateral sclerosis: a randomised, double-blind, placebo-controlled trial. *Lancet Neurol* 2017;16:505–12.
- Miller RG, Mitchell JD, Lyon M, et al. Riluzole for amyotrophic lateral sclerosis (ALS) / motor neuron disease (MND). *Cochrane Database Syst Rev* 2007;CD001447.
- Smith R, Pioro E, Myers K, et al. Enhanced bulbar function in amyotrophic lateral sclerosis: the nuedexta treatment trial. *Neurotherapeutics* 2017;14:762–72.
- Paganoni S, Hendrix S, Dickson SP, et al. Long-Term survival of participants in the CENTAUR trial of sodium phenylbutyrate-taurursodiol in amyotrophic lateral sclerosis. *Muscle Nerve* 2021;63:31–9.
- Al-Chalabi A, Hardiman O, Kiernan MC, et al. Amyotrophic lateral sclerosis: moving towards a new classification system. *Lancet Neurol* 2016;15:1182–94.
- Burrell JR, Halliday GM, Kril JJ, et al. The frontotemporal dementia-motor neuron disease continuum. *Lancet* 2016;388:919–31.
- Cooper-Knock J, Harvey C, Zhang S, et al. Advances in the genetic classification of amyotrophic lateral sclerosis. *Curr Opin Neurol* 2021;34:756–64.
- Vucic S, Higashihara M, Sobue G, et al. ALS is a multistep process in South Korean, Japanese, and Australian patients. *Neurology* 2020;94:e1657–63.
- Al-Chalabi A, Hardiman O. The epidemiology of ALS: a conspiracy of genes, environment and time. *Nat Rev Neurol* 2013;9:617–28.
- Ryan M, Heverin M, McLaughlin RL, et al. Lifetime risk and heritability of amyotrophic lateral sclerosis. *JAMA Neurol* 2019;76:1367–74.
- van Rheenen W, van der Spek RAA, Bakker MK, et al. Common and rare variant association analyses in amyotrophic lateral sclerosis identify 15 risk loci with distinct genetic architectures and neuron-specific biology. *Nat Genet* 2021;53:1636–48.
- de Boer EMJ, Orié VK, Williams T, et al. TDP-43 proteinopathies: a new wave of neurodegenerative diseases. *J Neurol Neurosurg Psychiatry* 2020;92:86–95.
- Tan RH, Ke YD, Ittner LM, et al. ALS/Ftld: experimental models and reality. *Acta Neuropathol* 2017;133:177–96.
- Ma XR, Prudencio M, Koike Y, et al. Tdp-43 represses cryptic exon inclusion in the FTD-ALS gene UNC13A. *Nature* 2022;603:124–30.
- Brown A-L, Wilkins OG, Keuss MJ, et al. Tdp-43 loss and ALS-risk SNPs drive mis-splicing and depletion of UNC13A. *Nature* 2022;603:131–7.
- Renton AE, Chiò A, Traynor BJ. State of play in amyotrophic lateral sclerosis genetics. *Nat Neurosci* 2014;17:17–23.
- Smukowski SN, Maioli H, Latimer CS, et al. Progress in amyotrophic lateral sclerosis gene discovery. *Neurol Genet* 2022;8:e669.
- Visscher PM, Brown MA, McCarthy MI, et al. Five years of GWAS discovery. *Am J Hum Genet* 2012;90:7–24.
- Rich KA, Roggenbuck J, Kolb SJ. Searching far and genome-wide: the relevance of association studies in amyotrophic lateral sclerosis. *Front Neurosci* 2020;14:603023.
- Shatunov A, Mok K, Newhouse S, et al. Chromosome 9p21 in sporadic amyotrophic lateral sclerosis in the UK and seven other countries: a genome-wide association study. *Lancet Neurol* 2010;9:986–94.
- van Es MA, Veldink JH, Saris CGJ, et al. Genome-Wide association study identifies 19p13.3 (UNC13A) and 9p21.2 as susceptibility loci for sporadic amyotrophic lateral sclerosis. *Nat Genet* 2009;41:1083–7.
- Laaksovirta H, Peuralinna T, Schymick JC, et al. Chromosome 9p21 in amyotrophic lateral sclerosis in Finland: a genome-wide association study. *Lancet Neurol* 2010;9:978–85.
- DeJesus-Hernandez M, Mackenzie IR, Boeve BF, et al. Expanded GGGGCC hexanucleotide repeat in noncoding region of C9orf72 causes chromosome 9p-linked FTD and ALS. *Neuron* 2011;72:245–56.
- Altshuler D, Daly MJ, Lander ES. Genetic mapping in human disease. *Science* 2008;322:881–8.
- Tam V, Patel N, Turcotte M, et al. Benefits and limitations of genome-wide association studies. *Nat Rev Genet* 2019;20:467–84.
- Diekstra FP, van Vught PWJ, van Rheenen W, et al. UNC13A is a modifier of survival in amyotrophic lateral sclerosis. *Neurobiol Aging* 2012;33:630.
- Ahmeti KB, Ajroud-Driss S, Al-Chalabi A, et al. Age of onset of amyotrophic lateral sclerosis is modulated by a locus on 1p34.1. *Neurobiol Aging* 2013;34:357.
- Vidal-Taboada JM, Lopez-Lopez A, Salvado M, et al. UNC13A confers risk for sporadic ALS and influences survival in a Spanish cohort. *J Neurol* 2015;262:2285–92.
- van Rheenen W, Shatunov A, Dekker AM, et al. Genome-wide association analyses identify new risk variants and the genetic architecture of amyotrophic lateral sclerosis. *Nat Genet* 2016;48:1043–8.
- Nicolas A, Kenna KP, Renton AE, et al. Genome-wide analyses identify KIF5A as a novel ALS gene. *Neuron* 2018;97:1268–83.
- Karczewski KJ, Francioli LC, Tiao G, et al. The mutational constraint spectrum quantified from variation in 141,456 humans. *Nature* 2020;581:434–43.
- Iida A, Takahashi A, Deng M, et al. Replication analysis of snps on 9p21.2 and 19p13.3 with amyotrophic lateral sclerosis in east asians. *Neurobiol Aging* 2011;32:757.
- Chen X, Huang R, Chen Y, et al. Association analysis of four candidate genetic variants with sporadic amyotrophic lateral sclerosis in a Chinese population. *Neurol Sci* 2014;35:1089–95.
- Yang B, Jiang H, Wang F, et al. UNC13A variant rs12608932 is associated with increased risk of amyotrophic lateral sclerosis and reduced patient survival: a meta-analysis. *Neurol Sci* 2019;40:2293–302.
- Tan HHG, Westeneng H-J, van der Burgh HK, et al. The distinct traits of the UNC13A polymorphism in amyotrophic lateral sclerosis. *Ann Neurol* 2020;88:796–806.
- Chiò A, Mora G, Restagno G, et al. UNC13A influences survival in Italian amyotrophic lateral sclerosis patients: a population-based study. *Neurobiol Aging* 2013;34:357.
- Placek K, Baer GM, Elman L, et al. UNC13A polymorphism contributes to frontotemporal disease in sporadic amyotrophic lateral sclerosis. *Neurobiol Aging* 2019;73:190–9.
- Ferrari R, Hernandez DG, Nalls MA, et al. Frontotemporal dementia and its subtypes: a genome-wide association study. *Lancet Neurol* 2014;13:686–99.
- Pottier C, Ren Y, Perkerson RB, et al. Genome-Wide analyses as part of the International FTL-TDP whole-genome sequencing Consortium reveals novel disease risk factors and increases support for immune dysfunction in FTL. *Acta Neuropathol* 2019;137:879–99.

- 42 Govaarts R, Beeldman E, Kampelmacher MJ, *et al.* The frontotemporal syndrome of ALS is associated with poor survival. *J Neurol* 2016;263:2476–83.
- 43 Diekstra FP, Van Deerlin VM, van Swieten JC, *et al.* C9orf72 and UNC13A are shared risk loci for amyotrophic lateral sclerosis and frontotemporal dementia: a genome-wide meta-analysis. *Ann Neurol* 2014;76:120–33.
- 44 Karch CM, Wen N, Fan CC, *et al.* Selective genetic overlap between amyotrophic lateral sclerosis and diseases of the frontotemporal dementia spectrum. *JAMA Neurol* 2018;75:860–75.
- 45 Brenner S. The genetics of *Caenorhabditis elegans*. *Genetics* 1974;77:71–94.
- 46 Brose N, Hofmann K, Hata Y, *et al.* Mammalian homologues of *Caenorhabditis elegans* unc-13 gene define novel family of C2-domain proteins. *J Biol Chem* 1995;270:25273–80.
- 47 Koch H, Hofmann K, Brose N. Definition of Munc13-homology-domains and characterization of a novel ubiquitously expressed Munc13 isoform. *Biochem J* 2000;349:247–53.
- 48 Quade B, Camacho M, Zhao X, *et al.* Membrane bridging by Munc13-1 is crucial for neurotransmitter release. *eLife* 2019;8:1–30.
- 49 Betz A, Thakur P, Junge HJ, *et al.* Functional interaction of the active zone proteins Munc13-1 and Rim1 in synaptic vesicle priming. *Neuron* 2001;30:183–96.
- 50 Varoqueaux F, Sigler A, Rhee J-S, *et al.* Total arrest of spontaneous and evoked synaptic transmission but normal synaptogenesis in the absence of Munc13-mediated vesicle priming. *Proc Natl Acad Sci U S A* 2002;99:9037–42.
- 51 Zarebidaki F, Camacho M, Brockmann MM, *et al.* Disentangling the roles of rim and Munc13 in synaptic vesicle localization and neurotransmission. *J Neurosci* 2020;40:9372–85.
- 52 Siksou L, Varoqueaux F, Pascual O, *et al.* A common molecular basis for membrane docking and functional priming of synaptic vesicles. *Eur J Neurosci* 2009;30:49–56.
- 53 Lai Y, Choi UB, Leitz J, *et al.* Molecular mechanisms of synaptic vesicle priming by Munc13 and Munc18. *Neuron* 2017;95:591–607.
- 54 Südhof TC. Neurotransmitter release: the last millisecond in the life of a synaptic vesicle. *Neuron* 2013;80:675–90.
- 55 Magdziarek M, Bolembach AA, Stepien KP, *et al.* Re-Examining how Munc13-1 facilitates opening of syntaxin-1. *Protein Sci* 2020;29:1440–58.
- 56 Ma C, Li W, Xu Y, *et al.* Munc13 mediates the transition from the closed syntaxin–Munc18 complex to the SNARE complex. *Nat Struct Mol Biol* 2011;18:542–9.
- 57 Grushin K, Kalyana Sundaram RV, Sindelar CV, *et al.* Munc13 structural transitions and oligomers that may choreograph successive stages in vesicle priming for neurotransmitter release. *Proc Natl Acad Sci U S A* 2022;119:e2121259119.
- 58 Varoqueaux F, Sons MS, Plomp JJ, *et al.* Aberrant morphology and residual transmitter release at the Munc13-deficient mouse neuromuscular synapse. *Mol Cell Biol* 2005;25:5973–84.
- 59 Basu J, Betz A, Brose N, *et al.* Munc13-1 C1 domain activation lowers the energy barrier for synaptic vesicle fusion. *J Neurosci* 2007;27:1200–10.
- 60 Wang S, Li Y, Gong J, *et al.* Munc18 and Munc13 serve as a functional template to orchestrate neuronal SNARE complex assembly. *Nat Commun* 2019;10:69.
- 61 Reddy-Alla S, Böhme MA, Reynolds E, *et al.* Stable positioning of unc13 restricts synaptic vesicle fusion to defined release sites to promote synchronous neurotransmission. *Neuron* 2017;95:1350–64.
- 62 Hilton BJ, Husch A, Schaffran B, *et al.* An active vesicle priming machinery suppresses axon regeneration upon adult CNS injury. *Neuron* 2022;110:51–69.
- 63 Rhee JS, Betz A, Pyott S, *et al.* Beta phorbol ester- and diacylglycerol-induced augmentation of transmitter release is mediated by Munc13s and not by PKCs. *Cell* 2002;108:121–33.
- 64 Yang Y, Calakos N. Munc13-1 is required for presynaptic long-term potentiation. *J Neurosci* 2011;31:12053–7.
- 65 Camacho M, Basu J, Trimbuch T, *et al.* Heterodimerization of Munc13 C₂A domain with RIM regulates synaptic vesicle docking and priming. *Nat Commun* 2017;8:15293.
- 66 He E, Wierda K, van Westen R, *et al.* Munc13-1 and Munc18-1 together prevent NSF-dependent de-priming of synaptic vesicles. *Nat Commun* 2017;8:15915.
- 67 Dittman JS. Unc13: a multifunctional synaptic marvel. *Curr Opin Neurobiol* 2019;57:17–25.
- 68 Junge HJ, Rhee J-S, Jahn O, *et al.* Calmodulin and Munc13 form a Ca²⁺ sensor/effector complex that controls short-term synaptic plasticity. *Cell* 2004;118:389–401.
- 69 Calloway N, Gouzer G, Xue M, *et al.* The active-zone protein Munc13 controls the use-dependence of presynaptic voltage-gated calcium channels. *eLife* 2015;4:1–15.
- 70 Lipstein N, Chang S, Lin K-H, *et al.* Munc13-1 is a Ca²⁺-phospholipid-dependent vesicle priming hub that shapes synaptic short-term plasticity and enables sustained neurotransmission. *Neuron* 2021;109:3980–4000.
- 71 Engel AG, Selcen D, Shen X-M, *et al.* Loss of Munc13-1 function causes microcephaly, cortical hyperexcitability, and fatal myasthenia. *Neurol Genet* 2016;2:e105.
- 72 Lipstein N, Verhoeven-Duif NM, Michelassi FE, *et al.* Synaptic UNC13A protein variant causes increased neurotransmission and dyskinesia movement disorder. *J Clin Invest* 2017;127:1005–18.
- 73 Tziortzouda P, Van Den Bosch L, Hirth F. Triad of TDP43 control in neurodegeneration: autoregulation, localization and aggregation. *Nat Rev Neurosci* 2021;22:197–208.
- 74 Ling JP, Pletnikova O, Troncoso JC, *et al.* Tdp-43 repression of nonconserved cryptic exons is compromised in ALS-FTD. *Science* 2015;349:650–5.
- 75 Prasad A, Bharathi V, Sivalingam V, *et al.* Molecular mechanisms of TDP-43 misfolding and pathology in amyotrophic lateral sclerosis. *Front Mol Neurosci* 2019;12:25.
- 76 Imaizumi K, Ideno H, Sato T, *et al.* Pathogenic mutation of TDP-43 impairs RNA processing in a cell type-specific manner: implications for the pathogenesis of ALS/FTLD. *ENEURO* 2022;9:ENEURO.0061-22.2022.
- 77 Devlin A-C, Burr K, Boroah S, *et al.* Human iPSC-derived motoneurons harbouring TARDBP or C9orf72 ALS mutations are dysfunctional despite maintaining viability. *Nat Commun* 2015;6:5999.
- 78 Dyer MS, Reale LA, Lewis KE, *et al.* Mislocalisation of TDP-43 to the cytoplasm causes cortical hyperexcitability and reduced excitatory neurotransmission in the motor cortex. *J Neurochem* 2021;157:1300–15.
- 79 Diaper DC, Adachi Y, Sutcliffe B, *et al.* Loss and gain of Drosophila TDP-43 impair synaptic efficacy and motor control leading to age-related neurodegeneration by loss-of-function phenotypes. *Hum Mol Genet* 2013;22:1539–57.
- 80 Henstridge CM, Sideris DI, Carroll E, *et al.* Synapse loss in the prefrontal cortex is associated with cognitive decline in amyotrophic lateral sclerosis. *Acta Neuropathol* 2018;135:213–26.
- 81 van de Bospoort R, Farina M, Schmitz SK, *et al.* Munc13 controls the location and efficiency of dense-core vesicle release in neurons. *J Cell Biol* 2012;199:883–91.
- 82 Vardar G, Chang S, Arancillo M, *et al.* Distinct functions of syntaxin-1 in neuronal maintenance, synaptic vesicle docking, and fusion in mouse neurons. *J Neurosci* 2016;36:7911–24.
- 83 Tao C-L, Liu Y-T, Zhou ZH, *et al.* Accumulation of dense core vesicles in hippocampal synapses following chronic inactivity. *Front Neuroanat* 2018;12:1–11.
- 84 D'Erchia AM, Gallo A, Manzari C, *et al.* Massive transcriptome sequencing of human spinal cord tissues provides new insights into motor neuron degeneration in ALS. *Sci Rep* 2017;7:10046.
- 85 Katsu M, Hama Y, Utsumi J, *et al.* MicroRNA expression profiles of neuron-derived extracellular vesicles in plasma from patients with amyotrophic lateral sclerosis. *Neurosci Lett* 2019;708:134176.
- 86 Fornai F, Longone P, Cafaro L, *et al.* Lithium delays progression of amyotrophic lateral sclerosis. *Proc Natl Acad Sci U S A* 2008;105:2052–7.
- 87 Morrison KE, Dhariwal S, Hornabrook R, *et al.* Lithium in patients with amyotrophic lateral sclerosis (lials): a phase 3 multicentre, randomised, double-blind, placebo-controlled trial. *Lancet Neurol* 2013;12:339–45.
- 88 Verstraete E, Veldink JH, Huisman MHB, *et al.* Lithium lacks effect on survival in amyotrophic lateral sclerosis: a phase IIb randomised sequential trial. *J Neurol Neurosurg Psychiatry* 2012;83:557–64.
- 89 Chiò A, Mora G. The final chapter of the ALS lithium SAGA. *Lancet Neurol* 2013;12:324–5.
- 90 van Eijk RPA, Jones AR, Sproviero W, *et al.* Meta-Analysis of pharmacogenetic interactions in amyotrophic lateral sclerosis clinical trials. *Neurology* 2017;89:1915–22.
- 91 Willemse SW, Roes KCB, Van Damme P, *et al.* Lithium carbonate in amyotrophic lateral sclerosis patients homozygous for the C-allele at SNP rs12608932 in UNC13A: protocol for a confirmatory, randomized, group-sequential, event-driven, double-blind, placebo-controlled trial. *Trials* 2022;23:978.
- 92 Forlenza OV, De-Paula VJR, Diniz BSO. Neuroprotective effects of lithium: implications for the treatment of Alzheimer's disease and related neurodegenerative disorders. *ACS Chem Neurosci* 2014;5:443–50.
- 93 Limanaqi F, Biagioni F, Ryskalin L, *et al.* Molecular mechanisms linking ALS/FTD and psychiatric disorders, the potential effects of lithium. *Front Cell Neurosci* 2019;13:450.
- 94 Pasquali L, Longone P, Isidoro C, *et al.* Autophagy, lithium, and amyotrophic lateral sclerosis. *Muscle Nerve* 2009;40:173–94.
- 95 Ito D. Promise of nucleic acid therapeutics for amyotrophic lateral sclerosis. *Ann Neurol* 2022;91:13–20.
- 96 Perrone B, La Cognata V, Sprovieri T, *et al.* Alternative splicing of ALS genes: misregulation and potential therapies. *Cell Mol Neurobiol* 2020;40:1–14.
- 97 Finkel RS, Mercuri E, Darras BT, *et al.* Nusinersen versus sham control in infantile-onset spinal muscular atrophy. *N Engl J Med* 2017;377:1723–32.
- 98 Lopez ER, Borschel WF, Traynor BJ. New antisense oligonucleotide therapies reach first base in ALS. *Nat Med* 2022;28:25–7.
- 99 Blanco FA, Czizkora A, Kedeei N, *et al.* Munc13 is a molecular target of bryostatin 1. *Biochemistry* 2019;58:3016–30.
- 100 van Eijk RPA, Eijkemans MJC, Nikolakopoulos S, *et al.* Pharmacogenetic interactions in amyotrophic lateral sclerosis: a step closer to a cure? *Pharmacogenomics J* 2020;20:220–6.
- 101 Kiernan MC, Vucic S, Talbot K, *et al.* Improving clinical trial outcomes in amyotrophic lateral sclerosis. *Nat Rev Neurol* 2021;17:104–18.