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RESEARCH ARTICLE

In Vivo Molecular Signatures of Cerebellar Pathology in Spinocerebellar Ataxia Type 3

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ABSTRACT: Background: No treatment exists for the most common dominantly inherited ataxia Machado-Joseph disease, or spinocerebellar ataxia type 3 (SCA3). Successful evaluation of candidate therapeutics will be facilitated by validated noninvasive biomarkers of disease pathology recapitulated by animal models.
Objective: We sought to identify shared in vivo neurochemical signatures in two mouse models of SCA3 that reflect the human disease pathology.
Methods: Cerebellar neurochemical concentrations in homozygous YACMJD84.2 (Q84/Q84) and hemizygous CMVMJD135 (Q135) mice were measured by in vivo magnetic resonance spectroscopy at 9.4 tesla. To validate the neurochemical biomarkers, levels of neurofilament medium (NFL; indicator of neuroaxonal integrity) and myelin basic protein (MBP; indicator of myelination) were measured in cerebellar lysates from a subset of mice and patients with SCA3. Finally, NFL and MBP levels were measured in the cerebellar extracts of Q84/Q84 mice upon silencing of the mutant *ATXN3* gene.
Results: Both Q84/Q84 and Q135 mice displayed lower *N*-acetylaspartate than wild-type littermates, indicating neuroaxonal loss/dysfunction, and lower *myo*-inositol and total choline, indicating disturbances in phospholipid membrane metabolism and demyelination. Cerebellar NFL and MBP levels were accordingly lower in both models as well as in the cerebellar cortex of patients with SCA3 than controls. Importantly, *N*-acetylaspartate and total choline correlated with NFL and MPB, respectively, in Q135 mice. Long-term sustained RNA interference (RNAi)-mediated reduction of *ATXN3* levels increased NFL and MBP in Q84/Q84 cerebella.
Conclusions: *N*-acetylaspartate, *myo*-inositol, and total choline levels in the cerebellum are candidate biomarkers of neuroaxonal and oligodendrocyte pathology in SCA3, aspects of pathology that are reversible by RNAi therapy.
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Key Words: ataxin-3; demyelination; Machado-Joseph disease; magnetic resonance spectroscopy; polyglutamine

With increasing human lifespan, numerous age-related neurodegenerative diseases of diverse etiologies are becoming more prevalent. Nine such disorders are caused by an expanded CAG triplet repeat in genes that encode an abnormally longer polyglutamine (polyQ) tract in the respective disease proteins.[1,2] Since the identification of these disease genes in the 1990s, an increased understanding of the molecular basis of polyQ disorders led to several potentially efficacious therapies that were tested in animal models. The nucleotide-based reduction of CAG-containing transcripts has proven to be a particularly compelling therapeutic strategy for polyQ diseases in preclinical studies,[3-7] and clinical trials are underway for Huntington's disease using antisense oligonucleotides.[8] Other gene and pharmacological therapeutic approaches for polyQ disorders are also

[Correction added on July 14, 2020 after first online publication: Figure 1 updated.]

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in the pipeline.[9-11] The readiness for these upcoming clinical trials depends on the availability of disease biomarkers that allow noninvasive monitoring of aspects of cerebral disease pathology to assess therapeutic efficacy.

Spinocerebellar ataxia type 3 (SCA3) or Machado-Joseph disease (MJD) is a polyQ disease caused by an expanded CAG repeat in the *ATXN3* gene[12] that leads to the selective dysfunction and loss of neurons of specific nuclei in the cerebellum, brainstem, midbrain, spinal cord, and peripheral nerves.[9-11,13-21] The disease manifests in patients with SCA3 as ataxia and a variable degree of other manifestations, including extrapyramidal signs, neuropathy, ophthalmoplegia, and muscle atrophy.[22-26]

SCA3 is one of the polyQ diseases for which clinical trials are forthcoming. Antisense oligonucleotides,[27-30] other RNA interference molecules,[31,32] and pharmacological agents such as the selective serotonin reuptake inhibitor citalopram[33-35] showed preclinical efficacy to mitigate molecular, pathological, and phenotypic SCA3-like signs in transgenic mice.

The success of upcoming human trials of these agents will be facilitated by the availability of validated noninvasive biomarkers of cerebral and cerebellar pathology. To this end, a number of studies have demonstrated an ability to detect macro-structural, micro-structural, and neurochemical abnormalities noninvasively by magnetic resonance imaging[14,36-38] (MRI) and spectroscopy[39-41] (MRS) in SCA3. Although macrostructural disease-associated changes detectable by conventional MRI clearly mark tissue loss, other magnetic resonance (MR) metrics may allow the noninvasive monitoring of aspects of pathology that precede cell loss and atrophy and hence may be reversible with treatments. However, such MR metrics need to be validated by comparing them to tissue pathology.

Here, using MRS at 9.4 tesla (T), we sought to identify cerebellar neurochemical signatures in the following two mouse models of SCA3 that are extensively used in SCA3 preclinical trials: homozygous YACMJD84.2 (Q84/Q84)[31,42] and hemizygous CMVMJD135 (Q135)[43] mice. We assessed the two models to identify the common neurochemical abnormalities that may provide signatures of SCA3 pathology. To validate the identified potential neurochemical biomarkers and determine which aspects of pathology they reflect, we evaluated cerebellar demyelination and neuroaxonal pathology in the same mice as well as brain tissue from patients with SCA3. Finally, we determined whether RNA interference (RNAi)-mediated silencing of the SCA3 gene reverses cerebellar demyelination and axonopathy in the Q84/Q84 model because evidence of reversibility would suggest that noninvasive myelin and neuronal markers could reflect therapeutic efficacy in future trials.

Materials and Methods

Experimental Design

The study was designed to assess the MRS neurochemical profiles of two transgenic models frequently used in preclinical trials for SCA3:Q84/Q84[42] and Q135[43] mice. All animal procedures were approved by the University of Michigan Committee on the Use and Care of Animals (Protocol PRO00003836) and by the University of Minnesota Institutional Animal Care and Use Committee (Protocol 1207A17510). Groups of Q84/Q84 (N = 14 [7 females/7 males], 9–17 months old) and their littermate nontransgenic (wild-type [wt]) mice (N = 11 [7 female/4 male], 11–18 months old) and Q135 (N = 9 [3 females/6 males], 8–16 months old) and their wt littermates (N = 8 [5 females/3 males], 10–16 months old) in the C57Bl6/J background (Supplementary Table 1) were scanned. Mice were housed in cages of a maximum of five animals and maintained in a standard 12-hours light/dark cycle with food and water ad libitum. Peripheral blood was collected by tail vein snip for a subgroup of Q84/Q84 mice (N = 5) and littermate controls (N = 4) to analyze liver profiles. Mice were shipped from the University of Michigan to the University of Minnesota for MR scanning 2 to 4 weeks prior to scans. After MR scanning, the mice were deeply anesthetized with sodium pentobarbital (100 mg/kg intraperitoneal) and sacrificed by transcardial perfusion with pH 7.4 phosphate buffered saline, and the tissues were sent back to the University of Michigan for postmortem analyses for demyelination (myelin basic protein [MBP], Luxol fast blue) and axonopathy (neurofilament medium [NFL]) and for the assessment of molecular layer thickness and Purkinje cell count.

To investigate if the pathological features identified in the SCA3 mice reflect the human condition, we obtained deidentified frozen and fixed samples from the cerebellar cortex of autopsied brains from molecularly confirmed SCA3 (N = 6) and control individuals (N = 5) from the University of Michigan Brain Bank (see Supplementary Table 2 for demographic information).

To verify if RNAi-mediated depletion of human mutant *ATXN3* rescues cerebellar molecular phenotypes in SCA3 mice, we used protein lysates from cerebella of end-stage Q84/Q84 mice (10–20 months old) that, at 6 to 8 weeks of age, were injected in the deep cerebellum nuclei with an adeno-associated virus encoding an artificial microRNA targeting mutant

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ATXN3 (miRATXN3) (N = 10) or with vehicle (N = 10).[31]

Mouse Genotyping and $(CAG)_n$ Size Assessment

Genotyping was performed by polymerase chain reaction using DNA isolated from tail biopsy at weaning as previously described.[42,43] $(CAG)_n$ size in Q84/Q84 and Q135 mice (Supplementary Table 1) and in SCA3 and control individuals (Supplementary Table 2) was determined at Laragen Inc. (Culver City, CA) by gene fragment analysis.

In Vivo Measurements

MR Protocol

Procedures for anesthesia and MR scanning were identical to our prior studies.[44,45] Mice were induced with 3% to 4% isoflurane and were maintained anesthetized with 1.5% to 2% isoflurane during scanning. Body temperature was maintained at 36°C to 37°C and respiration rate at ~70 to 100 breaths per minute. The scanning time for each animal was approximately 50 minutes. MR scans were performed using a quadrature surface radio frequency coil and a 9.4 T/31 cm magnet (Magnex Scientific, Abingdon, UK) interfaced to an Agilent console (Agilent, Inc., Palo Alto, CA). A cerebellar volume of interest (VOI; 5–7 μL, placed based on anatomical landmarks to avoid inclusion of cerebrospinal fluid; Figs. 1A, 2A) was selected on coronal and sagittal multislice images obtained with a rapid acquisition with relaxation enhancement sequence.[46] First-order and second-order shims were adjusted using fast automatic shimming technique by mapping along projections.[47] Localized ^{1}H-MR spectra were acquired with a localization by adiabatic selective refocusing sequence (echo time = 15 milliseconds, repetition time = 5 seconds, 256 averages)[48] as described previously.[44,45] Spectra were saved as single scans, which were frequency and phase corrected.[49] Frequency drifts were corrected in the time domain after peak picking in frequency domain (the total creatine peak at 3 ppm) by using the first transient as reference. Similarly, phase correction was done in the time domain by calculating the phase difference between the reference (first) transient and other transients. Transients that showed evidence for motion (substantial deviations in frequency, line width, signal-to-noise ratio, loss of water suppression efficiency relative to other transients) were excluded prior to averaging.[49] In the 23 spectra obtained from the Q84/Q84 cohort (mice that were included in the MRS analysis), 1 to 2 shots (of 256) were excluded in 3 spectra, 45 shots were excluded in 1 spectrum, and the acquisition had to be stopped because of gasping in 1 mouse, generating 110 usable shots. The remaining 18 spectra had all 256 shots. In the 14 spectra obtained from the Q135 cohort (mice that were included in the MRS analysis), 5 shots were excluded in 1 spectrum, and 93 shots were excluded in another spectrum. The remaining 12 spectra had all 256 shots. Finally, the averaged spectra were corrected for eddy current effects using the unsuppressed water signal acquired from the same VOI.[50]

Metabolite Quantification

Metabolites were quantified using LCModel[51] relative to unsuppressed water spectra acquired from the same VOI, as described previously.[44,45] Reliable concentrations were selected based on Cramér-Rao lower bounds criteria (quantification with Cramér-Rao lower bounds ≤20% in the majority of the spectra). Alanine, aspartate, glycine, and scyllo-inositol were excluded from final analysis based on these criteria. If the correlation between two metabolites was consistently high (correlation coefficient < −0.5), their sum was reported.[52] Strong negative correlation was found between creatine and phosphocreatine and between glycerophosphocholine + phosphocholine, therefore total creatine and total choline (tCho) were reported. Based on these reliability criteria,14 concentrations were evaluated: ascorbate (Asc), γ-aminobutyric acid (GABA), glucose (Glc), glutamine (Gln), glutamate (Glu), glutathione (GSH), *myo*-inositol (myo-Ins), lactate (Lac), *N*-acetylaspartate (NAA), *N*-acetylaspartylglutamate (NAAG), phosphoethanolamine (PE), taurine (Tau), total creatine (tCr), and total choline (tCho).

Liver Profile

Peripheral blood collected from mouse tail vein snip was immediately centrifuged at maximum speed, and serum was collected and stored at −80°C. Serum samples were thawed and centrifuged, and supernatants were loaded in VetScan Mammalian Liver Profile reagent rotors (Abaxis, Inc., Union City, CA), which in turn were read in a VetScan Chemistry Analyzer providing quantitative determinations of albumin, alkaline phosphatase, alanine aminotransferase, bile acids, blood urea nitrogen, total cholesterol, gamma glutamyl transferase.

Postmortem Measurements

Western Blot

Extracts of soluble proteins in radioimmunoprecipitation assay buffer from mouse cerebella or human cerebellar cortex were obtained using an established protocol.[31] Lysates from soluble protein fractions were resolved on 10% sodium dodecyl sulfate polyacrylamide gel electrophoresis gels, and corresponding polyvinylidene difluoride membranes

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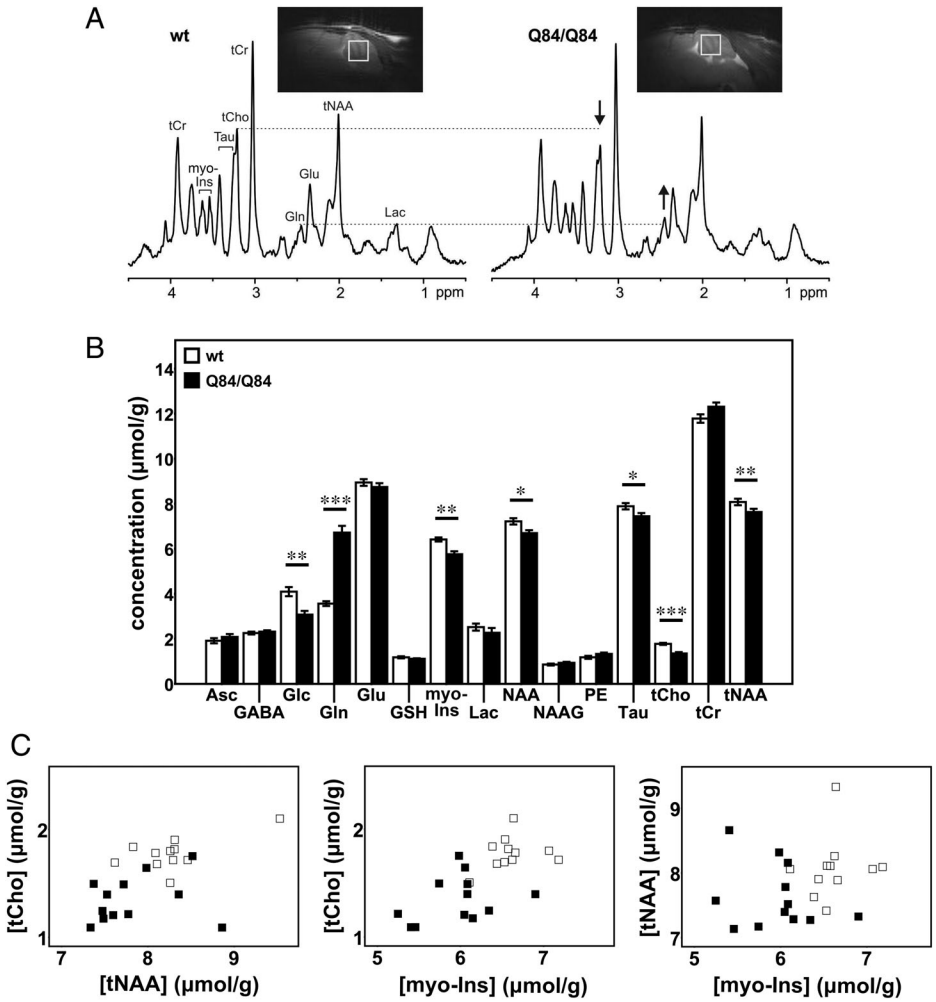

FIG. 1. Cerebellar neurochemical levels are altered in homozygous Q84/Q84 mice. (**A**) Representative localized proton magnetic resonance spectra and midsagittal T_2-weighted images of a Q84/Q84 and a wt littermate mouse. The most prominent neurochemical abnormalities, namely lower tCho and higher Gln in Q84/Q84 compared with wt mice, are denoted in the spectra by arrows. (**B**) Cerebellar neurochemical profiles of Q84/Q84 mice (N = 12, black bars) and wt littermates (N = 11, white bars). Bars represent average neurochemical concentration ± standard error of the mean. Comparison between mouse genotypes was performed using Student's *t* test and statistical significance is indicated as: $^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$. (**C**) Separation of Q84/Q84 mice (black squares) from controls (white squares) by plotting 2 altered metabolites against each other. Asc, ascorbate; GABA, γ-aminobutyric acid; Glc, glucose; Gln, glutamine; Glu, glutamate; GSH, glutathione; Lac, lactate; myo-Ins, *myo*-inositol; NAA, *N*-acetylaspartate; NAAG, *N*-acetylaspartylglutamate; PE, phosphoethanolamine; Q84, YACMJD84.2 mice; Tau, taurine; tCho, total choline; tCr, total creatine; tNAA, total NAA; wt, wild type.

were incubated overnight at 4°C with primary antibodies: rat anti-MBP (1:1000; MCA409S; AbDSerotec, Kidlington, UK), mouse anti-160kD NFL (1:1000; ab7794; Abcam, Cambridge, UK), rabbit anti-α-tubulin (1:5000; 2144S; Cell Signaling, Danvers, MA), mouse anti-GAPDH (1:10000; MAB374; Millipore, Burlington, MA), and rabbit anti-MJD (1:20000). Bound primary antibodies were visualized by peroxidase-conjugated anti-rat, anti-mouse, or anti-rabbit secondary antibodies (1:10000; Jackson ImmunoResearch Laboratories, West Grove, PA) followed by treatment with enhanced chemiluminescence-plus reagent (PerkinElmer, Waltham, MA) and exposure to autoradiography films. Band intensity was quantified by densitometry using ImageJ.

Luxol Fast Blue Staining

The 5-μm paraffin sections of cerebellar lobules from aged-matched patients with SCA3 and unaffected individuals were simultaneously deparaffinized in xylene and stained with Luxol fast blue. Briefly, the sections were dewaxed in xylene, washed in absolute ethanol and 95% ethanol, stained overnight in 0.1% Luxol fast blue in acidic 95% ethanol, washed in 95% ethanol, differentiated in 0.05% lithium carbonate solution for 30 seconds, rinsed in distilled water and washed in 70% and 90% ethanol, washed in absolute ethanol, fixed in xylene, and mounted in dibutylphthalate polystyrene xylene mountant. Slides were imaged in a bright-field BX51 microscope (Olympus, Center Valley, PA).

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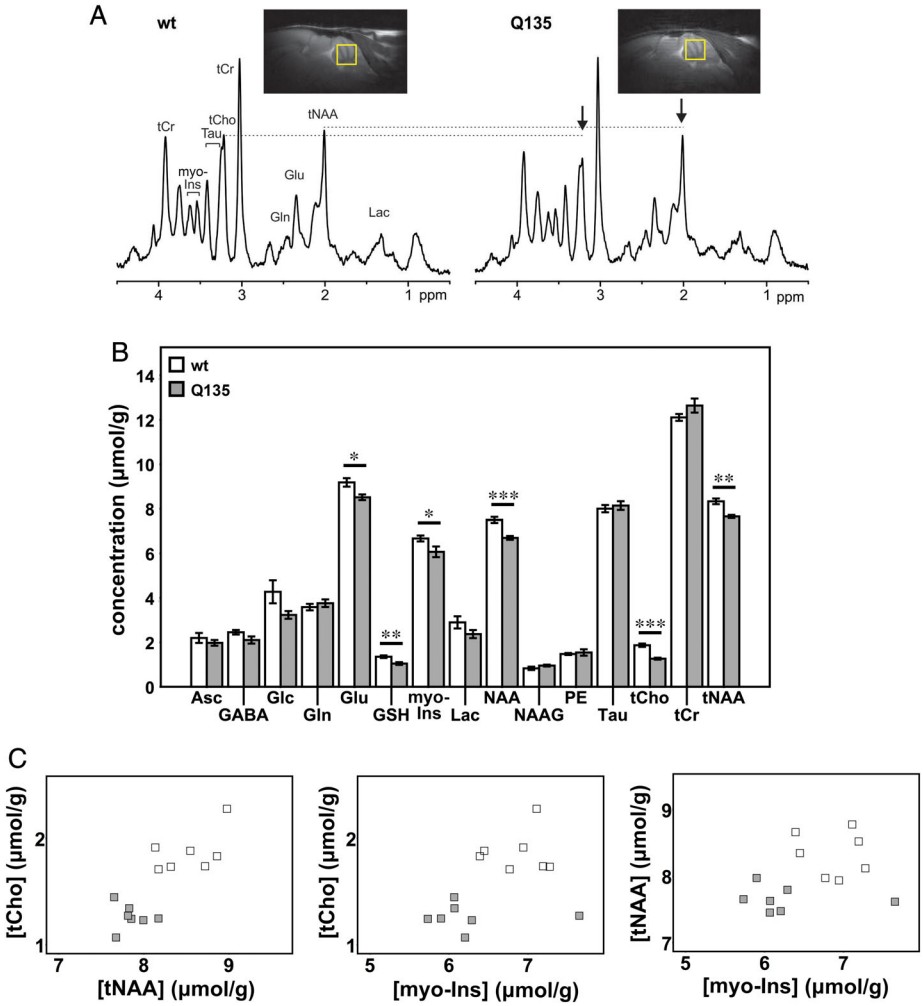

FIG. 2. Cerebellar neurochemical levels are altered in hemizygous Q135 mice. (**A**) Representative localized proton magnetic resonance spectra and midsagittal T_2-weighted images of a Q135 and a wt littermate mouse. The most prominent neurochemical abnormalities, namely lower tCho and tNAA in Q135 compared with wt mice, are denoted in the spectra by arrows. (**B**) Cerebellar neurochemical profiles of Q135 mice (N = 7, gray bars) and wt littermates (N = 7, white bars). Bars represent average chemical concentration ± standard error of the mean. Comparison between mouse genotypes was performed using Student's *t* test and statistical significance is indicated as: $^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$. (**C**) Separation of Q135 mice (gray squares) from controls (white squares) by plotting 2 altered metabolites against each other. Asc, ascorbate; GABA, γ-aminobutyric acid; Glc, glucose; Gln, glutamine; Glu, glutamate; GSH, glutathione; Lac, lactate; myo-Ins, *myo*-inositol; NAA, *N*-acetylaspartate; NAAG, *N*-acetylaspartylglutamate; PE, phosphoethanolamine; Q135, CMVMJD135 mice; Tau, taurine; tCho, total choline; tCr, total creatine; tNAA, total NAA; wt, wild type. [Color figure can be viewed at wileyonlinelibrary.com]

Immunofluorescence Staining

Left mouse brain hemispheres were fixed overnight in 4% paraformaldehyde, embedded in 30% sucrose/phosphate-buffered saline, and sectioned on a sledge microtome (SM200R; Leica Biosystems, Richmond, IL). Triple immunofluorescent labelling of free-floating 40-μm sagittal sections was conducted as previously[31] using rat anti-MBP (1:50), mouse anti-NFL (1:500), rabbit anti-ATXN3 (anti-MJD 1:2000), secondary mouse Alexa Fluor 488, rat Alexa Fluor 568 antibodies, and rabbit Alexa Fluor 647 (Invitrogen, Carlsbad, CA), and 4,6-diamidino-2-phenylindole (DAPI). Sections were mounted with Prolong Gold Antifade Reagent (Invitrogen, Carlsbad, CA, USA) and imaged in an IX71 microscope (Olympus, Center Valley, PA). Measurements of molecular layer thickness were made as previously described.[53] Briefly, using images from the triple immunostaining, two measurements were made at the depth of the primary fissure and two others at 100 μm from there. Purkinje neuron cell counts were obtained as the total number of neurons in the region of the primary fissure folium.

Liver Hematoxylin and Eosin Histology

Livers from four Q84/Q84 mice and one littermate control used in the MRS studies were fixed in 10% formalin and paraffin embedded, and 4-μm paraffin sections were stained with hematoxylin and eosin and observed in a bright field microscope.

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Statistical Analysis

Characteristics of the transgenic and control groups were compared using the two-tailed, unpaired Student's *t* test for age and spectral quality metrics (line width and signal-to-noise ratio obtained from LCModel) and chi-square test for sex. Levels of neurochemicals and proteins were compared between the transgenic and control groups using Student's *t* test as all distributions were normal and showed homogeneous variances. Linear regression analyses were performed to evaluate the relationship between neurochemical concentrations and protein levels using Pearson correlation. A $P < 0.05$ was considered statistically significant in all analyses. *P* values were not corrected across the multiple metabolites as a result of the exploratory nature of our analysis and to avoid inflation of type II errors. Data were analyzed using IBM (Armonk, NY) SPSS Statistics 22 software.

Results

Homozygous Q84/Q84 and Hemizygous Q135 Transgenic Mice Show Shared Neurochemical Alterations in the Cerebellum as Measured by In Vivo MRS

Q84/Q84 and Q135 SCA3 transgenic mice show early onset of SCA3-like phenotypes starting around 6 weeks of age[31,43] and therefore are often used in preclinical trials.[31,35,43,53-56] We investigated common neurochemical biomarkers in these two models that could serve as outcome measures in preclinical trials.

Because no in vivo no MRS studies were previously conducted in SCA3 mouse models, we obtained MR spectra at ultra-high field from the cerebellar vermis of symptomatic homozygous Q84/Q84, hemizygous Q135, and their littermate wt controls at an age when Purkinje cell dysfunction and pathology were previously shown in related transgenic mouse models.[35,53] Two Q84/Q84 mice, two Q135 mice, and one Q135 wt control were found to have an abnormal high Gln profile that was previously described in the brains of mice derived from the C57BL/6 strain.[57,58] The abnormal profile consisted of 2-fold to 3-fold higher Gln, 35% to 60% lower myo-Ins, and 10% to 35% lower taurine relative to other wt or SCA3 mice in the same group. Because this profile results from portosystemic shunting in the liver,[57] which causes alterations in gene expressions in many organs, these five mice were excluded from further analysis.

SCA3 transgenic mice and their wt controls included in the MRS analyses were matched for age (Q84/Q84 13.4 ± 2.1 [mean ± standard deviation] vs. wt 13.7 ± 2.0 months, $P = 0.71$; Q135 14.7 ± 3.0 vs. wt 15.1 ± 2.3 months, $P = 0.77$) and sex (Q84/Q84 7 males/5 females vs. wt 4 males/7 females, $P = 0.41$; Q135 4 males/3 females vs. wt 2 males/5 females, $P = 0.59$). In addition, spectral quality was comparable in the SCA3 vs. wt groups (line widths Q84/Q84 10.0 ± 2.2 (mean ± standard deviation) vs. wt 9.7 ± 1.5 Hz, $P = 0.67$; Q135 12.6 ± 4.1 vs. wt 10.3 ± 1.5 Hz, $P = 0.19$; signal-to-noise ratio Q84/Q84 30.6 ± 7.6 vs. wt 31.7 ± 4.0, $P = 0.67$; Q135 28.7 ± 3.5 vs. wt 27.4 ± 3.2, $P = 0.49$). Finally, structural images did not indicate substantial atrophy in the SCA3 vs. wt mice (Figs. 1A and 2A), and the VOI did not contain cerebrospinal fluid. Therefore, the group differences observed in the neurochemical profiles could not be attributed to group differences in age, sex, atrophy, or spectral quality.

Neurochemical profiles of Q84/Q84 mice (N = 12), with predominant CAG repeat size ranging from 69 to 74 triplets (Supplementary Table 1), showed significantly higher Gln and lower levels of total NAA (tNAA), NAA, glucose, myo-Ins, taurine, and tCho compared with wt littermates (N = 11) (Fig. 1A,B). Because sex matching was imperfect between groups and the severity of the phenotype may be sex dependent in SCA3 mice, we further investigated the neurochemical profiles of male and female mice only. We observed the same neurochemical trends in male and female mice analyzed separately, except for the myo-Ins difference that appeared to be primarily driven by female mice (Supplementary Fig. 1). This was consistent with a lack of sex differences of the motor phenotype in Q84/Q84 mice.[31] To investigate if the Gln levels in Q84/Q84 mice that were almost two times higher than their wt controls were the result of liver dysfunction, we analyzed serum liver profiles and liver pathology in a subgroup of the mice included in the MRS analysis. These analyses revealed typical liver histology with no signs of portosystemic shunt in four Q84/Q84 mice (data not shown) and normal levels of liver analytes in mice of both genotypes (Supplementary Table 3) except in one wt mouse that showed bile acids >250 μmol/L, but normal liver hematoxylin and eosin histology (data not shown), thereby excluding liver dysfunction as the cause of the detected high levels of Gln in Q84/Q84 transgenic mice.

Cerebellar neurometabolite profiles of Q135 mice (N = 7), with CAG repeat length ranging from 125 and 129 trinucleotides (Supplementary Table 1), revealed significantly lower levels of tNAA, NAA, Glu, myo-Ins, glutathione, and tCho compared with controls (N = 7) (Fig. 2A,B). Similar to the Q84/Q84 mice, the same neurochemical trends were observed in male and female Q135 mice analyzed separately (Supplementary Fig. 2). Therefore, lower NAA and tNAA, tCho, and myo-Ins represent the common neurochemical abnormalities in both SCA3 models (Supplementary Fig. 3). In addition, groups of Q84/Q84 and Q135 mice were separated from wt controls with little or no overlap by plotting

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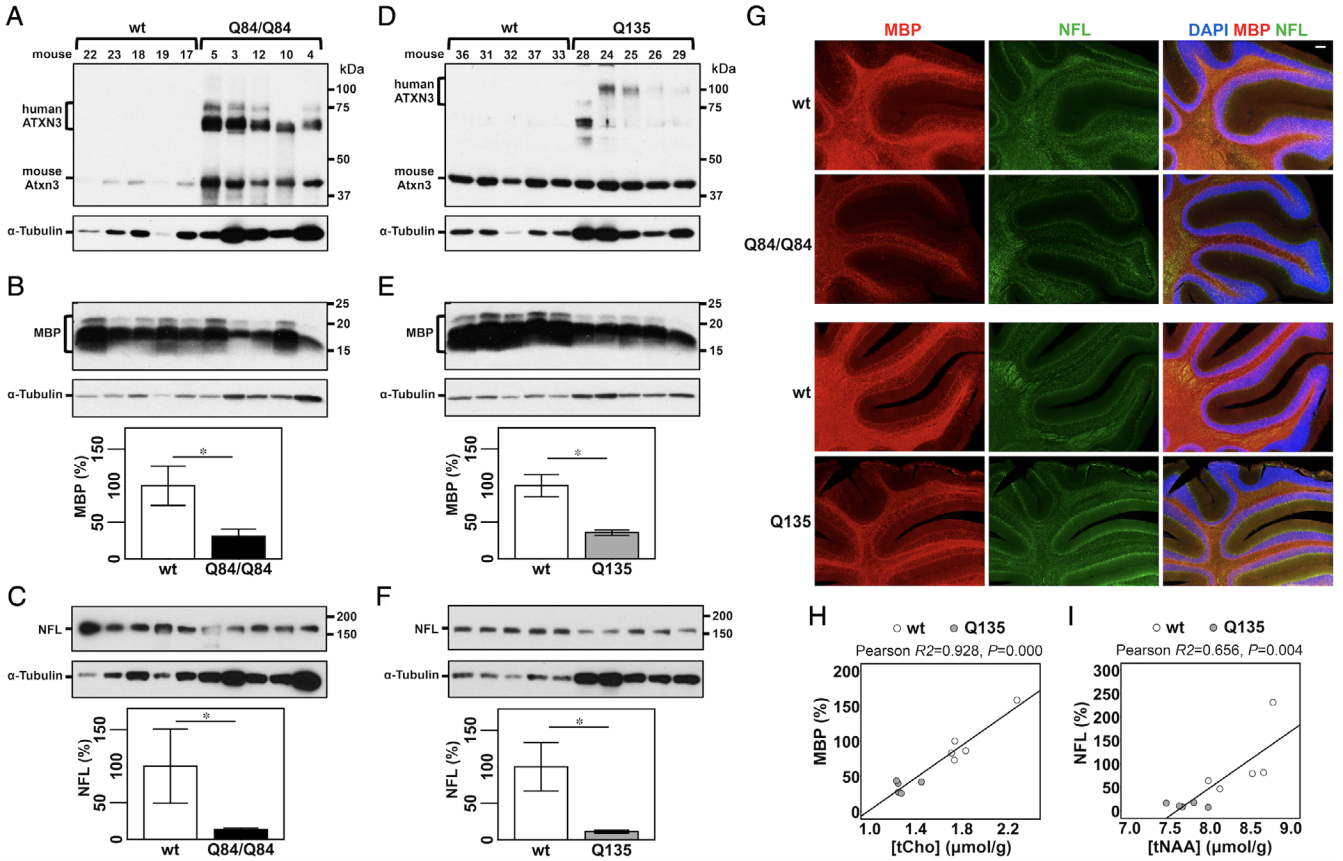

FIG. 3. Cerebella of SCA3 transgenic mice show decreased levels of MBP and NFL that correlate with concentrations of tCho and tNAA, respectively, in Q135 mice. (**A,D**) Anti-*ATXN3* immunoblot (anti–Machado-Joseph disease antibody) detecting mutant human *ATXN3* and endogenous mouse Atxn3 in cerebellar soluble protein extracts of the subset of Q84/Q84 (**A**), Q135 (**D**), and corresponding littermate wt mice used to assess levels of MBP (**B,E**) and NFL medium (**C,F**). Western blots show decreased levels of MBP and NFL in the cerebella of Q84/Q84 (**B,C**) and Q135 (**E,F**) compared with controls. Graphs show quantification of protein bands by densitometry. Bars represent the average percentage of protein relative to respective wt controls normalized for α-tubulin (± standard error of the mean). Statistical significance determined by Student's *t* test is indicated as $^{*}P < 0.05$. (**G**) Representative images of immunofluorescent labelling of MBP (red) and NFL (green) show decreased signal of these two proteins in the cerebella of Q84/Q84 and Q135 mice compared with corresponding littermates (N = 4 mice per group). Nuclei were labeled with 4,6-diamidino-2-phenylindole dihydrochloride (blue). Scale bar, 100 μm. (**H,I**) Plots showing Pearson correlations of levels of MBP with tCho (**H**) and NFL with tNAA (**I**) in Q135 (gray circles) and their respective wt littermate mice (white circles). DAPI, 4,6-diamidino-2-phenylindole dihydrochloride; MBP, myelin basic protein; NFL, neurofilament medium; Q84, YACMJD84.2 mice; Q135, CMVMJD135 mice; tCho, total choline; tNAA, total NAA; wt, wild-type. [Color figure can be viewed at wileyonlinelibrary.com]

concentrations of these metabolites against each other (Fig. 1C,2C).

SCA3 Transgenic Mice Show Depletion of MBP and NFL in Cerebellar Extracts and Slices and Thinning of the Molecular Layer

Because the three neurochemicals that allowed clear separation of both SCA3 transgenic mouse models from their respective controls suggest disturbances in the metabolism of membrane and myelin phospholipids[59,60] (myo-Ins and Cho) and neuroaxonal pathology[61] (NAA) and were all decreased in the cerebella of SCA3 mice, we investigated whether these mice show cerebellar demyelination and axonal atrophy (Fig. 3).

Immunoblot analysis of cerebellar protein extracts from a subset (N = 5 per group, 3 females/2 males) of the mice used to obtain neurochemical profiles (Fig. 3A, D) revealed that the levels of MBP were indeed reduced to 31% of wt levels in Q84/Q84 mice (Fig. 3B) and to 35% of wt levels in Q135 mice (Fig. 3E). NFL abundance was also reduced to 13% of wt levels in the cerebella of Q84/Q84 mice (Fig. 3C) and to 11% of wt levels in Q135 mice (Fig. 3F). Decreased cerebellar levels of MBP and NFL in Q84/Q84 and Q135 mice compared with controls were further evidenced by the immunolabeling of these two proteins in the cerebellar slices of these mice (N = 4 animals per group) (Fig. 3G). Triple immunofluorescence staining of MBP, NFL, and *ATXN3* in the cerebella of this subset of mice further revealed a significantly thinner molecular layer in the Q84/Q84 and Q135 mice than the wt littermates (Supplementary Fig. 4A) and a similar number of Purkinje cells in the primary fissure folia of mice from all genotypes (Supplementary Fig. 4B).

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In Vivo Myelin and Neuronal Markers Measured by MRS Correlate With Postmortem Myelin and Neuronal Markers in SCA3 Transgenic Mice

We next sought to determine if levels of tCho and/or myo-Ins are indicators of the status of myelination and if tNAA levels reflect axon integrity in the cerebellum. Hence, we investigated correlations between the levels of these neurochemicals with the abundance of MBP and NFL proteins in the two SCA3 mouse models (Fig. 3H,I, Supplementary Fig. 5). Because of the small sample size per genotype group, correlation analyses were performed combining data from transgenic mice and corresponding wt littermates for each SCA3 transgenic mouse strain. The concentration of tCho correlated significantly with MBP levels (R^2 = 0.928, P < 0.001) (Fig. 3H), and levels of tNAA correlated significantly with NFL expression in the Q135 mice (R^2 = 0.656, P = 0.004) (Fig. 3I). To test if the significance of the tCho-MBP and tNAA-NFL correlations in Q135 mice was the result of a genotype clustering effect, we repeated the correlation analyses adjusting for the genotype. Although both correlations remained significant adjusting for genotype (tCho-MBP, R^2 = 0.929, P = 0.000; tNAA-NFL, R^2 = 0.658, P = 0.023), we verified that the MBP and tCho concentrations correlated independently of the genotype and that NFL correlated with tNAA levels as a result of a combined effect of tNAA and genotype. No correlation was found between tCho and MBP levels, tNAA and NFL concentrations in Q84/Q84 mice (Supplementary Fig. 5B,D), or myo-Ins and MBP levels in either mouse model (Supplementary Fig. 5A,C).

MBP and NFL Are Lower in the Cerebellar Cortex of Patients With SCA3 Than Healthy Controls

To investigate whether the dysregulation of cerebellar MBP and NFL in the two SCA3 transgenic mouse models reflects the human SCA3 condition, we assessed the levels of these proteins in samples from the cerebellar cortex of patients with SCA3 and healthy controls (Supplementary Table 2). Levels of MBP were decreased to 9% of control levels and NFL to 19% of control levels in the cerebellar cortex of patients with SCA3 (Fig. 4A–C), indicating demyelination and axonopathy in this brain region. Luxol fast blue staining of brains from patients with SCA3 and aged-matched unaffected individuals confirmed extensive

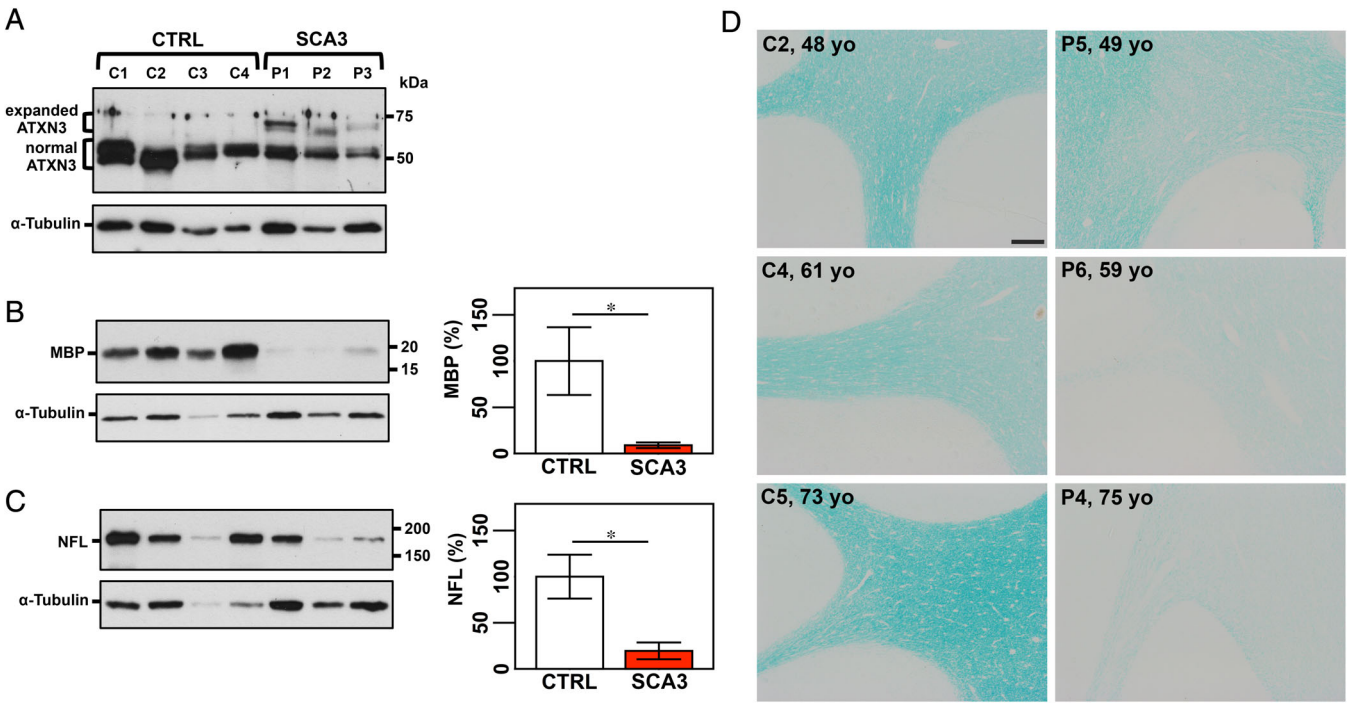

FIG. 4. Cerebellar lobules of patients with SCA3 show decreased levels of MBP and NFL medium and demyelination. (**A**) Anti-*ATXN3* immunoblot (anti–Machado-Joseph disease antibody) detecting expanded and normal *ATXN3* in soluble protein extracts from the cerebellar cortex of patients with SCA3 and control individuals. Detection of MBP (**B**) and NFL medium (**C**) by Western blotting shows lower levels of both proteins in patients compared with controls. Graphs show quantification of protein bands by densitometry. Bars represent the average percentage of protein relative to respective wild-type controls normalized for α-tubulin (± standard error of the mean). Statistical significance determined by Student's *t* test is indicated as $^*P < 0.05$. (**D**) Luxol fast blue staining of cerebellar sections shows signs of demyelination in patients with SCA3 compared with aged-matched unaffected individuals, which is more evident in older patients. Scale bar, 200 μm. C2, control 2; C4, control 4; C5, control 5; CTRL, control; MBP, myelin basic protein; NFL, neurofilament medium; P4, patient 4; P5, patient 5; P6, patient 6; SCA3, spinocerebellar ataxia type 3; yo, years old. [Color figure can be viewed at wileyonlinelibrary.com]

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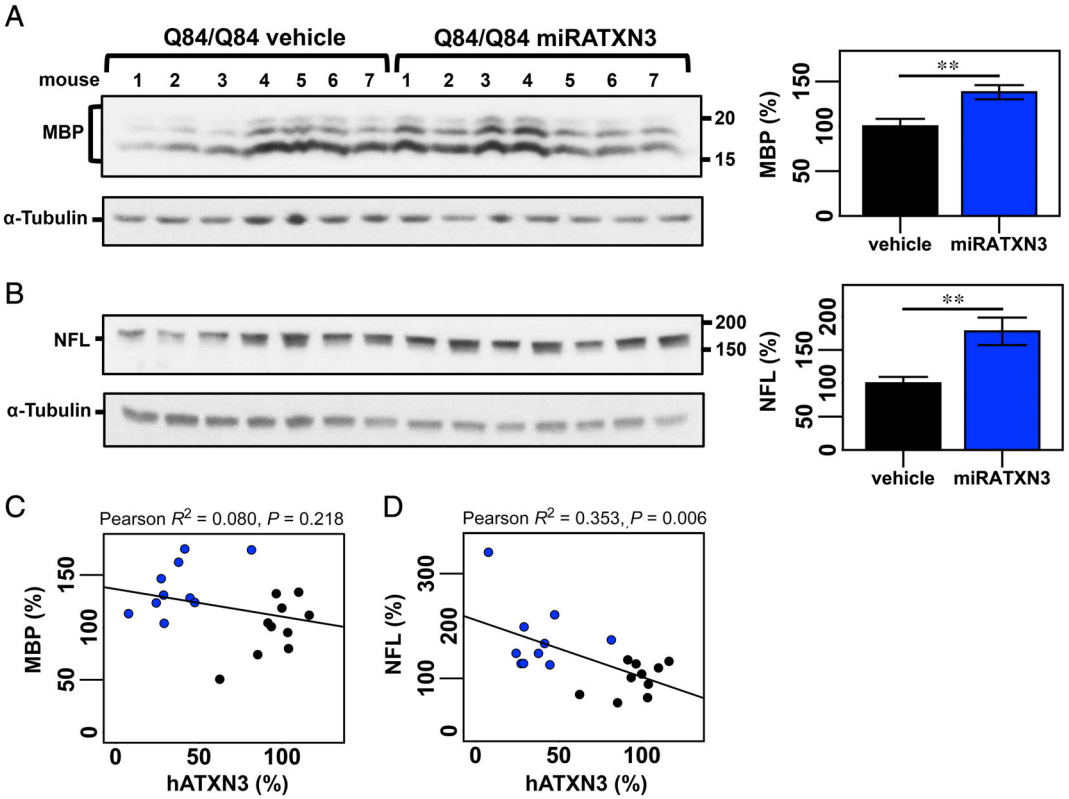

FIG. 5. Cerebella from miRATXN3-treated Q84/Q84 show higher levels of MBP and NFL medium compared to vehicle-treated Q84 animals. Immunoblotting to detect MBP (**A**) and NFL (**B**) in cerebellar soluble protein extracts from end-stage Q84/Q84 mice injected with an adeno-associated virus delivering an artificial microRNA targeting *ATXN3* transcripts (miRATXN3) or injected with vehicle. Graphs show quantification of protein bands by densitometry. Bars represent the average percentage of protein relative to levels in vehicle-injected Q84/Q84 mice, normalized for α-tubulin (± standard error of the mean). Black and blue bars indicate, respectively, vehicle-injected and miRATXN3-injected Q84/Q84 mice. Statistical significance determined by Student's *t* test is indicated as $^{**}P < 0.01$. Plots showing Pearson correlations of levels of MBP with hATXN3 (**C**) and of NFL with hATXN3 (**D**) in vehicle-treated (black circles) or miRATXN3-treated (blue circles) Q84/Q84 mice. hATXN3, human ATXN3; MBP, myelin basic protein; miRATXN3, microRNA targeting mutant ATXN3; NFL, neurofilament medium; Q84, YACMJD84.2 mice. [Color figure can be viewed at wileyonlinelibrary.com]

demyelination in the cerebella of patients with SCA3 that is more evident in aged patients (Fig. 4D).

Long-Term Sustained Reduction of Mutant *ATXN3* Rescues Cerebellar Myelination and Neurofilament Biomarkers in Homozygous Q84/Q84 Mice

Because approaches to reduce levels of *ATXN3* gene products are currently a promising candidate therapy for SCA3, we sought to evaluate whether long-term sustained RNAi-mediated decrease of mutant human *ATXN3* (hATXN3) abundance in Q84/Q84 cerebella would prevent the reduction of MBP and NFL. Therefore, we used cerebellar protein extracts from end-stage Q84/Q84 mice that were injected at 6 to 8 weeks of age in the deep cerebellar nuclei with an adeno-associated virus encoding an artificial microRNA targeting mutant *ATXN3* (miRATXN3).[31] We previously showed that miRATXN3 reduced hATXN3 levels to ~40% of the vehicle-injected Q84/Q84 mice.[31] The cerebella of miRATXN3-treated Q84/Q84 mice in fact showed increased MBP and NFL levels of, respectively, 137% and 177% of the levels in vehicle-treated Q84/Q84 mice (Fig. 5A,B). Whereas no association was detected between MBP and hATXN3 levels ($P = 0.218$) (Fig. 5C), the NFL levels were significantly correlated with levels of mutant hATXN3, demonstrating an association between the level of gene silencing and the extent of rescue of neuroaxonal pathology in the miRATXN3-treated Q84/Q84 mice ($P = 0.006$) (Fig. 5D).

Discussion

Future human clinical trials for SCA3 that seek to successfully translate preclinical animal studies would be facilitated by validated imaging biomarkers of cerebellar pathology. Here we identified shared neurochemical abnormalities in the homozygous Q84/Q84[31,42] and hemizygous Q135[43] transgenic mice. Both of these models are well-characterized models, reproduce several aspects of SCA3, and are extensively used in preclinical trials. We have further demonstrated associations of

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these noninvasive MR markers with protein markers of neuroaxonal pathology and demyelination as well as the reversibility of these pathologies with mutant *ATXN3* gene silencing.

Previously, cerebral and cerebellar metabolic alterations were only reported in one study that used in vitro ^{1}H-MRS in the brain tissue obtained from hemizygous Q84 mice.[62] The cerebellar neurometabolite spectra of homozygous Q84/Q84 mice showed similarities to those previously described in the in vitro study, namely, higher Gln and lower NAA, tCho, and myo-Ins in Q84/Q84 mice than in wt controls.[62] Furthermore, the lower levels of tNAA observed in both models, lower levels of Glu in Q135, and higher levels of Gln in Q84/Q84 mice compared with controls recapitulate prior observations in patients with SCA3.[39,41] The decrease of tNAA in the cerebellum is a common biomarker of neuronal dysfunction or loss displayed by patients affected with several SCAs (SCA1, SCA2, SCA3/MJD, SCA6, and SCA7),[39,41,63,64] SCA1 mouse models,[44,45,65] and hemizygous Q84 mice.[62] The decreased Glu levels detected suggests the dysfunction of glutamatergic granule cells, unipolar brush cells (UBCs), and/or parallel and climbing fibers in the cerebellar cortex.[66] Although the number or function of these glutamatergic cells has not been investigated in the cerebellar lobules of Q135 or Q84/Q84 mice, Purkinje cells show decreased calbindin staining in Q135 mice[35] and electrophysiological alterations in Q84 mice,[53] indicating that these cells are somehow dysfunctional. Because Purkinje cells receive excitatory input from parallel and/or climbing fibers, it is possible that Q135 Purkinje cells are impaired because of the decreased input from these fibers into the molecular layer. End-stage Q84/Q84 cerebella did not show decreased levels of Glu, but displayed increased concentration of Gln, which could suggest an abnormal Glu-Gln cycle between glutamate cells and Bergmann glia in the molecular layer and/or a higher number of glial cells that produce the bulk of Gln in the brain. Although cerebellar cell loss in aged SCA3 mice needs to be further investigated, the thinning of the molecular layer accompanied by preserved Purkinje cell number in these mice suggests that dysregulated levels of tNAA, Glu, and Gln reflect neuronal dysfunction and dendritic atrophy rather than cell loss in these models, similar to prior observations in SCA1 models.[44]

In addition to the previously described neurochemical changes in SCA3 mice, each of the transgenic mouse groups showed a clear separation from their respective wt controls in concentrations of tNAA, myo-Ins, and tCho in the cerebellum (Figs. 1C, 2C, Supplementary Fig. 3). NAA is a validated marker of neuronal viability[61] and a source of acetate for myelin lipid synthesis in oligodendrocytes,[67] myo-Ins is a structural sugar of membrane and myelin phospholipids,[39] and changes in tCho levels reflect disturbances in phospholipid metabolism.[67] Because all 3 metabolites were decreased in the spectra of both SCA3 mouse models, we hypothesized that these mice would display cerebellar demyelination and axon atrophy. Demyelination and white matter and axon dysfunction and axonopathy have indeed been reported histopathologically in brain tissue obtained from patients with SCA3[17,40,41] and primary oligodendrocyte/myelin dysfunction indicated by diffusion MRI in SCA3.[14] Furthermore, altered function of oligodendrocytes was recently reported in SCA3 models including the Q84.[68] Here, by showing that aged Q84/Q84 and Q135 cerebella and postmortem cerebellar cortex from patients with SCA3 display reduced levels of MBP and NFL compared with their respective controls, we confirmed demyelination and axon loss in SCA3 cerebella. The magnitude of reduction that we detected in NFL in the SCA3 cerebella relative to controls was markedly higher than the reduction in the in vivo neuronal marker tNAA. Similarly, the magnitude of reduction in MBP in SCA3 was substantially higher than the percent reduction in the MRS markers myo-Ins and tCho. This is likely because these neurochemicals have multiple roles, such as serving as metabolic intermediates and osmolytes, and therefore are less specific for neuroaxonal and myelin pathology than the postmortem protein markers. However, importantly, the associations between tCho with MBP levels and tNAA with NFL abundance in the Q135 mice suggest that tCho and tNAA levels reflect the status of myelination and axon integrity in the cerebellum of these mice. This evidence supports the inclusion of MRS evaluation of these neurochemicals in preclinical trials using Q84/Q84 and Q135 mice to evaluate the efficacy of therapeutic agents in rescuing SCA3 pathology.

Although the MBP levels were higher in the miR-ATXN3-treated Q84/Q84 cerebella than wt controls, concentrations of MBP and hATXN3 did not correlate, possibly indicating that adeno-associated virus miR-ATXN3 poorly transduced oligodendrocytes, as expected for this virus serotype.[69] Cerebellar axon loss seems to be, however, a consequence of expression of toxic-expanded *ATXN3* because the reduction of NFL concentration in the Q84/Q84 cerebella was suppressed by the long-term decrease of mutant *ATXN3* levels in the miRATXN3-treated Q84/Q84 mice. NFL levels significantly correlated with hATXN3 abundance in the cerebella of Q84/Q84 mice, suggesting that adeno-associated virus miRATXN3 effectively transduced and reduced hATXN3 in the majority of cerebellar neurons. Importantly, the reversal of the neuroaxonal pathology with RNAi-mediated reduction of *ATXN3* levels supports the use of noninvasive imaging markers of this pathology in future preclinical and clinical trials that evaluate similar gene silencing strategies. No MRS measurements are available for this set of RNAi-treated

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SCA3 mice.[31] Whether gene silencing will rescue the abnormal levels of the myelin and neuronal markers measured by MRS, similar to prior observations in SCA1 mice,[70] remains to be determined in future studies.

The ultra-high field strength MRI scanner we used in this study is not widely available for human trials that will likely use the widely available 3T platform. We previously demonstrated the feasibility of detecting neurochemical alterations in patients with SCAs at field strengths ranging from 3 to 7 T.[39,41,63,64,71] Specifically, neurochemical abnormalities were reliably detected in SCA3 at 3 T.[39] Thus, the current observations in SCA3 models can be obtained with 3 T technology when similar optimized methods are used for MRS data acquisition and analysis. We have further shown good test–retest reproducibility of cerebellar neurochemical concentrations at 3 T[72] and the 2-site reproducibility of cerebellar and brainstem neurochemical concentrations at 3 T.[73] Finally, these MRS methods are now being validated for clinical trial readiness in SCA3 in an international, multisite setting (https://readisca.org/).

In summary, we have identified novel neurochemical and molecular similarities between end-stage homozygous Q84/Q84, aged hemizygous Q135 mice, and patients with SCA3, further supporting the use of these mouse models in preclinical trials of SCA3. Similar to patients with SCA3, both transgenic models show neurochemical signatures indicative of neuronal dysfunction, dysregulation of glutamatergic systems, and myelin and neurite loss. We also provide molecular confirmation of cerebellar myelin and axon damage in SCA3 mice and patients and establish significant associations of select neurochemical markers with invasive measures of myelin and axon damage. It will be important to perform future longitudinal MRS and molecular and pathological studies in parallel to evaluate the progression of neurometabolite dysregulation and associated molecular and pathological outcomes in the cerebellum and other SCA3-affected brain areas of transgenic mice. These novel neurochemical alterations in SCA3 transgenic mice reflect important aspects of pathology and should enable noninvasive monitoring of pathology reversal in future preclinical trials of therapeutic agents for SCA3.

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Supporting Data

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