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Water T2 could predict functional decline in patients with dysferlinopathy

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Abstract

Background Water T2 ($T2_{H2O}$) mapping is increasingly being used in muscular dystrophies to assess active muscle damage. It has been suggested as a surrogate outcome measure for clinical trials. Here, we investigated the prognostic utility of $T2_{H2O}$ to identify changes in muscle function over time in limb girdle muscular dystrophies.

Methods Patients with genetically confirmed dysferlinopathy were assessed as part of the Jain Foundation Clinical Outcomes Study in dysferlinopathy. The cohort included 18 patients from two sites, both equipped with 3-tesla magnetic resonance imaging (MRI) systems from the same vendor. $T2_{H2O}$ value was defined as higher or lower than the median in each muscle bilaterally. The degree of deterioration on four functional tests over 3 years was assessed in a linear model against covariates of high or low $T2_{H2O}$ at baseline, age, disease duration, and baseline function.

Results A higher $T2_{H2O}$ at baseline significantly correlated with a greater decline on functional tests in 21 out of 35 muscles and was never associated with slower decline. Higher baseline $T2_{H2O}$ in adductor magnus, vastus intermedius, vastus lateralis, and vastus medialis were the most sensitive, being associated bilaterally with greater decline in multiple timed tests. Patients with a higher than median baseline $T2_{H2O}$ (>40.6 ms) in the right vastus medialis deteriorated 11 points more on the North Star Ambulatory Assessment for Dysferlinopathy and lost an additional 86 m on the 6-min walk than those with a lower $T2_{H2O}$ (<40.6 ms). Optimum sensitivity and specificity thresholds for predicting decline were 39.0 ms in adductor magnus and vastus intermedius, 40.0 ms in vastus medialis, and 40.5 ms in vastus lateralis from different sites equipped with different MRI systems.

Conclusions In dysferlinopathy, $T2_{H2O}$ did not correlate with current functional ability. However, $T2_{H2O}$ at baseline was higher in patients who worsened more rapidly on functional tests. This suggests that inter-patient differences in functional decline over time may be, in part, explained by different severities of the active muscle damage, assessed by $T2_{H2O}$ measure at baseline. Significant challenges remain in standardizing $T2_{H2O}$ values across sites to allow

determining globally applicable thresholds. The results from the present work are encouraging and suggest that $T2_{H2O}$ could be used to improve prognostication, patient selection, and disease modelling for clinical trials.

Keywords Magnetic resonance imaging; Water T2; Limb girdle muscular dystrophy; Limb girdle muscular dystrophy R2; Limb girdle muscular dystrophy 2B

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Introduction

Predicting functional decline in muscular dystrophies is a difficult task. There are many paediatric and adult onset forms of muscular dystrophy and they display highly variable rates of disease progression, yet few clues to the cause of the variability have been identified.[1] In some diseases, particularly the more rapidly progressive Duchenne muscular dystrophy (DMD), identifying current functional ability may suggest the next function to be lost, leading to a predictable set of disease milestones.[2,3] Biomarkers that correlate with current function can therefore predict the next step in disease progression in DMD.[4] However, in the slowly progressive limb girdle muscular dystrophies (LGMD), predicting short-term functional changes presents more of a challenge. Dysferlinopathy is a form of LGMD, most commonly described as LGMDR2 or Miyoshi myopathy (MMD1).[5,6] In this disease, from the same functional starting point, one patient may remain stable for 3 years, while another deteriorates significantly over only 1 year.[7,8]

Being able to predict progression of muscular dystrophies has several advantages. Patients may benefit from clearer expectations about the future and more tailored care. Moreover, for clinical trials aiming to demonstrate an effective intervention, it is important to have a well-matched cohort, or at least to understand the differences in anticipated disease progression without intervention.[9,10] As interventional therapies become a reality for the muscular dystrophies, the need to identify biomarkers able to predict upcoming functional decline has intensified.[11,12]

Magnetic resonance imaging (MRI) has been proposed as one such biomarker.[4,11–13] The most used sequences in clinics are both qualitative and include T1-weighted, which detects fatty replacement of the muscles, and fat-suppressed T2-weighted imaging, which signal is increased in several diseases being usually related to oedema and inflammation, although these can be masked by the presence of fatty infiltrations due to the fat suppression.[14] Although these sequences have been demonstrated to be useful for the diagnosis of patients with neuromuscular diseases, their interpretation can be biased and they lack reproducibility, which hampers their application in longitudinal follow-up studies designed over short periods of time.[15] In contrast, quantitative MRI methods such as Dixon-based fat-fraction (FF) mapping, which provides an objective measurement of the amount of fat present in the skeletal muscles, have been demonstrated to correlate with muscle function and to capture changes in muscle structure over short periods of time. Such methods are being implemented in natural history studies and also clinical trials.[15–17] However, its role as a predictor of changes in muscle function has not been demonstrated so far.

T2 mapping sequences have also been used to study changes in muscle structure in several neuromuscular diseases (NMDs). Skeletal muscle T2 is elevated in the presence of oedema, inflammation, and necrosis, as a consequence of increased water mobility and disrupted tissue ultrastructure. However, fatty replacement is a common pathway in the disease progression of most NMDs, which also results in increased T2 values, because the T2 of fat is much longer than that of muscle.[15,18] In order to assess the current status of the residual skeletal muscle tissue, independently from the irreversible end-stage fatty replacement, water T2 ($T2_{H2O}$) mapping methods have been developed, allowing the detection of inflammatory, oedematous, and necrotic features in fatty-infiltrated muscles.[19,20]

$T2_{H2O}$ is increased in several NMDs and its capacity to predict changes in muscle structure, mainly the fat replacement that follows muscle fibre loss, has been reported in several diseases.[21–24] Recent data from the Clinical Outcomes Study (COS) baseline visit suggest that $T2_{H2O}$ correlates with fatty replacement over time in dysferlinopathy patients, confirming the capacity of $T2_{H2O}$ to identify active damage leading to muscle fibre loss and expansion of fat tissue.[25] However, the capacity of $T2_{H2O}$ to identify patients who will experience a quicker and more severe clinical progression over a short period of time remains to be demonstrated. If it could be shown to predict progression, $T2_{H2O}$ could be used both in clinics to identify patients at risk of progression and also in clinical trials to select patients who may deteriorate over a short period of time and whose results could be more informative about the effectivity of experimental therapies.

We hypothesized that inter-patient variation in active muscle damage, assessed by $T2_{H2O}$, may underlie and predict subsequent differences in disease progression from the same functional starting point in patients with dysferlinopathy. In this paper, we assess a series of quantitative MRI parameters,

including FF, contractile cross-sectional area (cCSA), and $T2_{H2O}$ value, in each of the lower limb muscles and how they relate to subsequent disease progression in a range of functional and timed tests in patients with dysferlinopathy, to determine whether any of these parameters can be effectively used to predict muscle function loss.

Methods

Patients

Patients were selected from the Jain Foundation COS in dysferlinopathy.[26] COS is an international, multicentric, prospective natural history study involving 15 centres in the USA, Europe, Asia, and Oceania. COS recruited and assessed 182 patients over a 3-year period. Assessments performed included medical, physical therapist, biochemical, cardiovascular, and respiratory and MRI that were performed at baseline visit and then every year until Year 3. All patients had a diagnosis of dysferlinopathy, confirmed by genetic testing, with two pathogenic mutations or one pathogenic mutation and evidence of reduced dysferlin expression on a western blot of skeletal muscle and/or monocytes. The baseline, 1-year data, and 3-year functional progression and quantitative muscle MRI analysis have previously been published.[7,8,25]

We selected a cohort of patients seen at Newcastle and Paris to limit the impact of inter-site variability. These two sites had the largest number of patients with MRI results and have previously been shown to have high inter-site reliability. In order to identify if quantitative MRI measurement could predict changes in muscle function, we only included ambulant patients who completed a set of four functional assessments including the North Star Assessment for limb girdle-type muscular dystrophies [North Star Ambulatory Assessment for Dysferlinopathy (NSAD)], the 6-min walk test (smwt), the timed up and go (TUG) test, and the 10-m walk test (10MWT) at baseline, Year 1, and Year 3. The cohort included a total of 18 patients who had an NSAD score of more than 15 points (*Figure* 1).

Quantitative muscle magnetic resonance imaging: acquisition and processing of Dixon and $T2_{H2O}$ imaging data

Patients were imaged using 3.0-tesla MRI clinical scanners from two different vendors: Newcastle (Philips) and Paris (Siemens). MRI acquisition parameters were standardized across sites before the start of the study. Patients were positioned feet-first supine, and all MRI sequences were centred at one-third of the femur from the superior border of the patella and at the widest part of the calf. The acquisition protocol for FF and $T2_{H2O}$ mapping in the COS study has been recently reported.[25]

Water and fat images were reconstructed using in-house Matlab code (MathWorks, Natick, MA, USA), which incorporated hierarchical IDEAL (iterative decomposition of water and fat with echo asymmetry and least-squares estimation) and the Tsao–Jiang algorithm for separating multiple chemical species by hierarchical decomposition and direct estimation of phase.[27] Using the mean-square error (MSE) images, quantitative $T2_{H2O}$ maps were reconstructed based on a tri-exponential fitting procedure.[19,21] Regions of interest

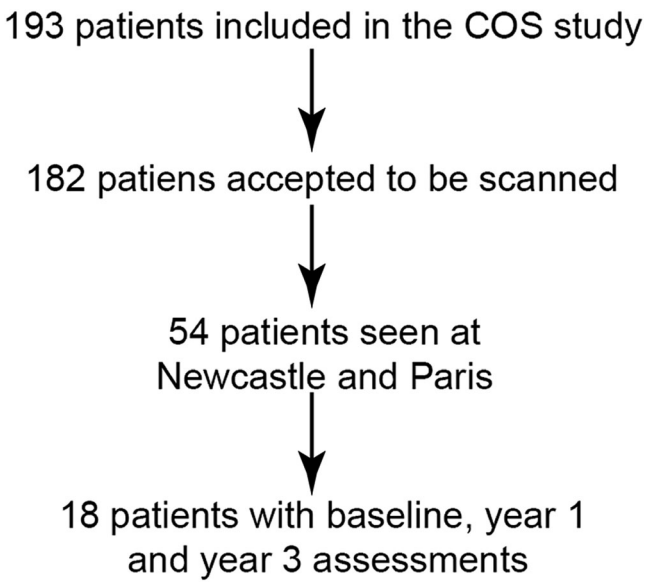

Figure 1 Patients included in this study from the original COS study. COS, Clinical Outcomes Study.

(ROIs) were drawn manually using a free software tool (https://www.itksnap.org) in the same five central slices on the shortest echo time (TE) image of the MSE series images by a single investigator as has been already described.[25] ROIs were drawn on both the left and right sides for seven leg muscles (extensor digitorum, tibialis anterior, tibialis posterior, peroneus longus, soleus, gastrocnemius medialis, and gastrocnemius lateralis) and in nine thigh muscles (vastus lateralis, vastus intermedius, vastus medialis, gracilis, sartorius, adductor magnus, biceps femoris long head, semimembranosus, and semitendinosus). For the determination of FF and cross-sectional area (CSA), the boundaries of the ROIs were drawn following individual muscle delineation, avoiding inclusion of other muscles, subcutaneous and intermuscular fat, tendons, and major blood vessels. cCSA was calculated for each muscle using $cCSA = (1 - FF_{mean}) * CSA$. For the assessment of $T2_{H2O}$, ROIs delineated the interior of the muscle, avoiding visible fasciae and blood vessels. ROIs that included <10 pixels were excluded for analysis.

After quality control, FF and cCSA calculation was not possible in all slices for all patients. This resulted in some slices for which there was a $T2_{H2O}$ value but not an FF and a cCSA value. Assessment of correlations between $T2_{H2O}$ and FF and cCSA used only those data sets where all variables were available (*n* numbers shown in *Table* 1).

Data analysis

Higher or lower than median $T2_{H2O}$

The median $T2_{H2O}$ of each muscle in each patient was categorized as either (a) greater than or equal to the cohort median $T2_{H2O}$ value for that muscle (high $T2_{H2O}$) or (b) less than the cohort median $T2_{H2O}$ value for that muscle (low $T2_{H2O}$). The change in functional score (ΔNSAD) or change in velocity in the timed tests (Δsmwt, ΔTUG, and Δ10MWT) over 3 years was calculated using assessments from baseline and Year 3.

Demographic information was reviewed, including age, disease duration, and baseline functional assessment score. Demographic data and baseline functional assessment results were compared between high and low $T2_{H2O}$ values in each muscle. Median values were compared between groups using a Mann–Whitney test.

For each functional assessment, a linear model of the change in functional score over 3 years was performed with high or low baseline $T2_{H2O}$ as a predictor and disease duration, age, and baseline functional score as covariates. Timed tests were assessed as velocities to give normally distributed values. This model produces an estimate of the additional change in functional score seen in those with a high $T2_{H2O}$ compared with those with a low $T2_{H2O}$ value, when disease duration, age, and baseline functional score are held constant. The analysis was performed for each functional assessment using the $T2_{H2O}$ value from each of the 16 muscles on each side in turn (4 functional assessments × 32 muscles—left and right). This method was repeated with FF and cCSA data. For each muscle, the change in FF and cCSA over 3 years was modelled against the baseline $T2_{H2O}$ value, with disease duration, age, and baseline FF and cCSA as covariates.

Differences were considered significant if the *P*-value was lower than 0.05. The *P*-values were adjusted using the Holm–Bonferroni correction to assess statistical significance in the presence of multiple comparisons.

Identifying a $T2_{H2O}$ threshold that identifies higher changes in North Star Ambulatory Assessment for Dysferlinopathy than expected

Previous studies modelling the COS cohort of patients over time have demonstrated that NSAD score declines by 1.68 points per year, and therefore, over 3 years, a decline of more than 5.04 points identifies those with faster than average functional decline.[8] Each patient was classed as having a decline of more than 5 points in NSAD score (positive result) or <5 points (negative result). We calculated the cut-off point in $T2_{H2O}$ with the higher sensitivity and specificity to distinguish between patients progressing more and less than 5 points in NSAD using receiver operating characteristic curves (ROC curves) using R software (https://www.r-project.org). We included in this analysis only those muscles whose baseline $T2_{H2O}$ correlated with changes in muscle function tests from baseline to the last visit assessment.

Results

Demographics

The cohort consisted of 18 ambulant patients (7 male) assessed in Newcastle (12 patients) or Paris (6 patients). Patients had a median age of 32.5 years (range 19–71 years) and had had symptoms for a median of 11 years (range 3–22 years). Demographic information split by $T2_{H2O}$ value per muscle is listed in Supporting Information, *Table S1*.

$T2_{H2O}$ values vary between muscles

Median $T2_{H2O}$ values varied from a minimum of 35.9 ms in gastrocnemius medialis (left) to a maximum of 42.7 ms in vastus lateralis (right) (*Table* 1). Within each muscle, $T2_{H2O}$ was not significantly different between left and right (Wilcoxon's test). $T2_{H2O}$ did not correlate with functional score, FF, or cCSA at baseline (*Table S2*).

Table 1 Correlation between $T2_{H2O}$ and changes in muscle function, fat fraction, and contractile cross-sectional area over 3 years

Muscle [left (L)/ right (R)]	Median $T2_{H2O}$ value (range)	ΔNSAD	Δ6MWT velocity in m/s	Δ6MWT distance in m	ΔTUG rate (event/s)	Δ10MWT velocity (m/s)	*N* with Dixon data	ΔFF (%)	ΔcCSA (mm^2)
Vastus intermedius (L)	40.0 (34.3–46.4	**−8***	**−0.18***	**−64.8***	**−0.04****	**−0.06***	16	9.4	−54.7
Vastus intermedius (R)	40.6 (35.8–47.2)	**−11****	−0.14	−50.4	**−0.04****	**−0.06****	16	7.8	−181.1
Vastus lateralis (L)	41.4 (27.3–48.0)	**−9****	−0.10	−36.0	**−0.03***	**−0.05***	16	8.4	−551.0
Vastus lateralis (R)	42.7 (35.2–51.4)	−6	−0.08	−28.8	**−0.03***	**−0.05***	16	**10.3***	−606.1
Vastus medialis (L)	39.5 (26.9–50.1)	**−8***	**−0.20***	**−72.0***	−0.02	**−0.05***	16	**9.8****	−315.9
Vastus medialis (R)	42.0 (33.1–48.8)	**−11****	**−0.24****	**−86.4****	**−0.04*****	**−0.07****	15	**9.7****	−441.4
Adductor magnus (L)	39.3 (33.1–45.8)	**−7***	−0.14	−50.4	**−0.03****	−0.04	16	15.5	−40.7
Adductor magnus (R)	39.0 (33.6–47.2	**−10****	**−0.18***	**−64.8***	**−0.04*****	**−0.07****	16	13.3	−156.9
Gracilis (L)	38.5 (33.4–43.0)	−4	−0.15	−54.0	**−0.03****	−0.03	16	9.1	−123.6
Gracilis (R)	37.5 (33.0–44.3)	−6	**−0.17***	**−61.2***	**−0.03****	−0.03	16	3.5	−141.9
Sartorius (L)	38.4 (32.0–43.9)	−4	**−0.16***	**−57.6***	**−0.03****	0	16	12.0	−142.6
Sartorius (R)	39.3 (34.5–44.8)	**−8****	−0.11	−39.6	**−0.03****	−0.03	16	7.9	−88.1
Biceps femoris (L)	39.6 (26.4–51.5)	−2	0.05	−18.0	−0.02	0.02	15	5.9	−162.9
Biceps femoris (R)	38.7 (27.7–50.4)	**−9****	−0.16	−57.6	**−0.03***	−0.02	14	13.6	−181.4
Semimembranosus (L)	38.3 (25.7–47.8)	**−7***	−0.13	−46.8	−0.03	−0.02	13	13.1	−113.1
Semimembranosus (R)	38.1 (20.3–46.2)	−3	−0.08	−28.8	−0.01	0.02	13	**10.0***	−168.7
Semitendinosus (L)	36.7 (28.8–44.6)	−5	−0.01	−3.6	−0.01	−0.01	16	7.1	−57.8
Semitendinosus (R)	34.8 (22.6–47)	−4	−0.09	−32.4	−0.01	0.01	16	9.4	−35.8
Tibialis anterior (L)	39.4 (23.9–49.4)	**−7***	−0.14	−50.4	−0.02	0	15	4.0	−41.1
Tibialis anterior (R)	38.6 (31.1–53.3)	−2	−0.04	−14.4	−0.01	0	15	−2.4	21.0
Extensor digitorum (L)	40.5 (34.2–50)	**−8***	−0.11	−39.6	**−0.03****	−0.01	15	**7.7***	−50.1
Extensor digitorum (R)	39.6 (34.8–48)	−2	−0.03	−10.8	−0.02	0.01	15	11.3	−95.3
Peroneus (L)	37.1 (23.9–50)	−2	−0.12	−43.2	−0.01	0.01	15	14.5	−159.6
Peroneus (R)	36.4 (25.2–48.2)	−3	−0.11	−39.6	0.02	−0.02	14	13.2	−184.5
Tibialis posterior (L)	40.2 (34.1–50.3)	−2	−0.11	−39.6	**−0.03***	0.01	15	6.9	−133.8
Tibialis posterior (R)	39.9 (34.8–48.3)	−4	−0.06	−21.6	−0.02	−0.02	15	8.4	−129.9
Soleus (L)	37.3 (23.6–50.4)	−1	−0.09	−32.4	−0.02	0.01	14	6.1	−14.9
Soleus (R)	38.1 (26.9–49.4)	**−9***	**−0.26****	**−93.6****	**−0.04****	−0.03	15	10.9	−40.5
Gastrocnemius lateralis (L)	36.9 (25.8–46.2)	5	0.03	10.8	0.01	0.02	14	14.1	−151.1
Gastrocnemius lateralis (R)	37.7 (23.1–47.6)	1	−0.06	−21.6	0	0	13	15.8	−34.0
Gastrocnemius medialis (L)	35.9 (26.2–57)	3	0.07	25.2	0.02	**0.05***	14	3.8	−95.1
Gastrocnemius medialis (R)	38.5 (26.1–60.7)	−4	−0.06	−21.6	−0.02	0	14	0.5	−73.8

N, number; Δ6MWT, change in 6-min walk test between Year 3 and baseline; Δ10MWT, change in 10-m walk test between Year 3 and baseline; ΔcCSA, change in contractile cross-sectional area between Year 3 and baseline; ΔFF, change in fat fraction between Year 3 and baseline; ΔNSAD, change in North Star Ambulatory Assessment for Dysferlinopathy between Year 3 and baseline; ΔTUG, change in timed up and go test between Year 3 and baseline.

The table shows mean changes in muscle function tests and their association with high $T2_{H2O}$. Regression coefficients in bold were statistically significant at the 0.05 level.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

High $T2_{H2O}$ value was significantly correlated with functional deterioration

Median $T2_{H2O}$ values at baseline significantly correlated with a worsening for at least one functional assessment over the next 3 years in 19 of the 32 muscles studied (*Table* 1). Muscles with high $T2_{H2O}$ were always associated with faster functional deterioration.

High $T2_{H2O}$ in adductor magnus and vastus intermedius/lateralis/medialis muscles stood out as being consistently and bilaterally significantly correlated with functional progression, demonstrating a greater deterioration in at least two functional assessments bilaterally (*Table* 1).

In vastus lateralis (bilateral), vastus medialis (right), semimembranosus (left), and extensor digitorum (left), median $T2_{H2O}$ values significantly correlated with an increase in FF over 3 years. Median $T2_{H2O}$ values did not correlate with a change in cCSA bilaterally in any muscle after 3 years of follow-up (*Table* 1).

Determining a $T2_{H2O}$ value for prediction

We studied the $T2_{H2O}$ value thresholds that maximized sensitivity and specificity for predicting decline in function using ROC curves of the adductor magnus, vastus intermedius, vastus lateralis, and vastus medialis. The $T2_{H2O}$ value thresholds obtained were 39.0 ms [88% sensitive and 75% specific, area under the curve (AUC) 0.847 (0.634–1)] in adductor magnus, 39.4 ms [100% sensitive, 60% specific, AUC 0.917 (0.782–1)] in vastus intermedius, 40.5 ms [94% sensitive, 70% specific, AUC 0.889 (0.734–1)] in vastus lateralis, and 40.1 ms [94% sensitive, 40% specific, AUC 0.875 (0.699–1)] in vastus medialis (*Figure* 2).

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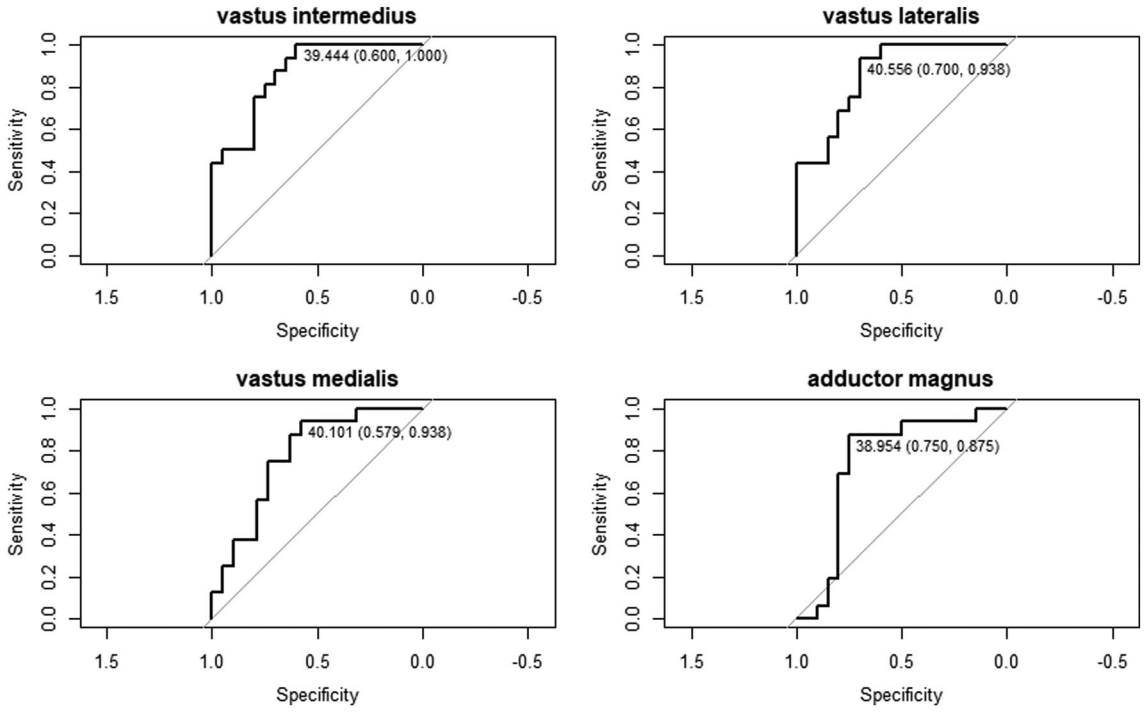

Figure 2 Receiver operating characteristic curve of the sensitivity and specificity achieved by all possible $T2_{H2O}$ relaxation times. The area under the curve is listed for each plot. In each curve, the threshold with the highest specificity (with zero false positives) and the threshold with optimum sensitivity and specificity are listed.

Table 2 Sensitivity and specificity of a $T2_{H2O}$ threshold in predicting decline in North Star Ambulatory Assessment for Dysferlinopathy (NSAD) score

Muscle	Threshold	Analysis	Decline of >1 point on NSAD in 1 year	Decline of >5 points on NSAD in 3 years
Adductor magnus	39.0 ms	Sensitivity	57%	63%
		Specificity	71%	78%
Vastus intermedius	39.4 ms	Sensitivity	86%	100%
		Specificity	57%	67%
Vastus lateralis	40.5 ms	Sensitivity	71%	88%
		Specificity	71%	78%
Vastus medialis	40.1 ms	Sensitivity	86%	88%
		Specificity	57%	67%
Muscle grouping				
All four muscles over threshold bilaterally	Respective threshold for each muscle as above	Sensitivity	43%	63%
		Specificity	71%	89%
At least one muscle over threshold bilaterally		Sensitivity	86%	100%
		Specificity	57%	56%

Validating $T2_{H2O}$ thresholds

Seventeen of the 18 patients had bilateral $T2_{H2O}$ results for adductor magnus, vastus intermedius, vastus lateralis, and vastus medialis and could be included in this analysis. The sensitivity of predicting decline on the NSAD score with the $T2_{H2O}$ thresholds over both 1 and 3 years is shown in *Table* 2 and *Figure* 3. As shown in *Table* 2, sensitivity and specificity of the measures suggested that those with high $T2_{H2O}$ values were generally rapid progressors. Sensitivity and specificity values weere not improved by requiring all four muscles to be over their indiviudal thresholds or requring only one of the four muscles to be over their individual theshold (*Table* 2).

Discussion

We have shown that a higher $T2_{H2O}$ in some muscles of the lower limbs might be associated with greater functional dete-

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rioration in patients with dysferlinopathy. These findings could be particularly helpful in advising patients about prognosis, in selecting patients for clinical trials, and, potentially, as an outcome measure for interventional trials.

There is a large body of evidence already published demonstrating that the amount of fat present in the skeletal muscle, which can be quantified using quantitative MRI (Dixon method) or proton magnetic resonance spectroscopy (^{1}H MRS), correlates with muscle function tests and is sensitive to change over short periods of time.[17,28] However, little is known about the relation of $T2_{H2O}$, which may be an indicator of active muscle damage and muscle function. It has been observed that in dysferlinopathy, the $T2_{H2O}$ does not correlate with baseline functional scores.[25] $T2_{H2O}$ has been shown to be impacted by high levels of FF (i.e. >60%) as also described in dysferlinopathy.[25] The data described in the current study, however, were acquired in exclusively ambulant patients, where FF values were predominantly lower than 60%. This suggests that $T2_{H2O}$ could be compared across patients at different stages of muscle loss to offer a snapshot of the current level of disease activity.

Higher than threshold baseline $T2_{H2O}$ value predicted greater decline over both 1 and 3 years, being consistently more accurate over the 3-year window. This suggests that change in function is a delayed downstream consequence of higher active muscle damage as quantified by the $T2_{H2O}$. This also reflects the slowly progressive nature of the disease, which results generally in small changes in function over 1 year but more consistently over a longer period of 3 years of follow-up. Despite this, even over a 1-year period, $T2_{H2O}$ thresholds were able to predict functional decline, which could make $T2_{H2O}$ particularly useful for detecting patients that will probably progress significantly during a clinical trial with a shorter running time.

We found a correlation between $T2_{H2O}$ at baseline and changes in FF in some of the investigated muscles, including the vastus medialis and the vastus intermedius. Correlation between muscle histopathology and quantitative MRI in patients with muscular dystrophy demonstrates histopathological features of inflammation appearing in the muscle, detectable by $T2_{H2O}$, before fat replacement begins.[29] In our population, it appears that active muscle damage, detected by higher $T2_{H2O}$, correlated with a functional decline in some of the muscles affected. Given the progressive nature of dysferlinopathy, we may anticipate that with a longer period of follow-up, this increased disease activity would ultimately translate into irreversibly increased FF and loss of cCSA. These findings suggest that $T2_{H2O}$ is a useful measure to demonstrate active muscle damage in remaining muscle in dysferlinopathy and to provide an accurate quantification of potentially salvageable tissue. This could be useful for monitoring response to future treatments, with $T2_{H2O}$ forming a potential early biomarker of treatment efficacy.[30]

However, not all the muscles imaged showed an association between higher $T2_{H2O}$ value and risk of more severe disease progression. The muscles in which $T2_{H2O}$ did not correlate with functional decline were those of the posterior compartment of the thigh and muscles of the leg, apart from the soleus. There are several possible reasons for this:

1. Due to the functional outcome measures chosen: The distal muscle that did show involvement was the soleus, which is heavily involved in walking, while the gastrocnemius and peroneus are less involved when walking on an even surface.[31] Regarding the posterior compartment of the thigh, walking can be maintained, even in the presence of significant weakness, by using compensatory mechanisms, which may mean that active muscle damage in these muscles does not translate to impairment on these specific outcome measures.[32]
2. Due to a lower degree of active muscle damage in these muscles at the time of assessment: The pattern of muscle involvement in dysferlinopathy includes an early and severe involvement of the soleus, both the gastrocnemius and the peroneus.[13] The first functional ability to be lost is usually the ability to stand on tiptoes, a function highly reliant on the gastrocnemius and soleus muscles.[33] The $T2_{H2O}$ values seen in these muscles were lower than those in the vasti muscles, and these muscles showed a higher fat replacement by the time of assessment as they are affected very early during the disease's progression.[13]
3. Due to the higher FF in these muscles: FFs in the posterior compartment of the thigh and the gastrocnemius were among the highest of all the muscles assessed (*Table S2*). $T2_{H2O}$ is much more heterogeneous in more fatty-replaced muscles, as has been shown.[34] In this sense, investigation in nine patients with more advanced dysferlinopathy and higher FFs found lower $T2_{H2O}$ in patients compared with healthy controls.[35] These data suggest that at those stages, $T2_{H2O}$ would probably not be useful to identify active muscle damage due to the massive replacement by fat.[34]

The association of $T2_{H2O}$ with functional test outcomes in specific muscles demonstrates the importance of selecting an appropriate 'reporter' muscle that is related to the functional outcome of interest and stage of disease progression. In this analysis, the muscles most associated with the timed tests and NSAD score were the vasti and the adductor magnus muscles. However, we may also anticipate that gluteal muscles, hip extensors, and abductors, which are important in rising from the floor and walking, may constitute useful reporter muscles.[31] Unfortunately, the COS study did not include $T2_{H2O}$ data from the gluteal muscles and so we were unable to investigate this further. As disease progresses, useful reporter muscles may change to those with lower FFs. In non-ambulant patients, where outcome measures focus

more on the upper limbs, which are generally preserved for longer in dysferlinopathy, one of the arm muscles may be a better reporter muscle.[10,13] We hope to address this in future, after completion of the clinical outcome extension study, which includes upper limb MRI.

We felt that it would be clinically useful for prognostication or trial cohort selection if a specific threshold could be defined above which $T2_{H2O}$ is considered 'high' and patients may be expected to progress more rapidly. We tried to validate these thresholds in a second cohort of dysferlin patients participating in COS study that were scanned in 3- and 1.5-tesla scanners at six other sites, but even though higher $T2_{H2O}$ levels were associated with faster progression, the accuracy, sensitivity, and specificity were lower as it is shown in the supporting information. There are many reasons that could explain these results including, among others, the different field strengths, which is known to affect the T2; the different vendor-specific sequence details such as radio frequency pulses and crusher-gradient schemes, which impact the measured magnetic resonance (MR) signal and hence the observed T2; and the transmitter and receiver coils that vary between vendors and even between system versions from the same vendor, which also impact the measured MR signal. While the scan protocols were standardized and the same post-processing methodology was used for all $T2_{H2O}$ data and was conducted by the same team, normalization across sites by means of control data from the same volunteers in all sites was not practicable.[15,16] We also attempted to correct for the difference in field strength by applying a correction factor based on published data to the results acquired on 1.5-tesla scanners.[36] However, this scaling factor is only an approximation that has been obtained in a few number of healthy controls and likely still leaves significant inter-scanner variability reinforcing the need of further research in this specific topic. In addition, besides hardware-related differences that affect T2, variations in patient status, such as recent exercise activity, are known to impact on the observed $T2_{H2O}$.[15] In this regard, patients participating in the COS study were imaged before physio assessments were performed and were asked to avoid doing any exercise the week before the visit. Most of the patients used a taxi to go to the hospital or imaging centre, in order to reduce the impact that the exercise could have in the MRI values, and were also asked to lie down before being scanned. The data obtained in our extension cohort (supporting information results) unfortunately do not allow us to take any final conclusion about what could be the causes of the lack of validation of the thresholds obtained, indicating that more research is needed in this topic. In this sense, we think that clinical or clinical trial-based applications attempting to use $T2_{H2O}$ for predicting disease progression across multiple sites would require additional research to identify the optimum standardization of scan protocol, $T2_{H2O}$ mapping, and normalization of data between sites before starting the trial.[37]

This study was conducted in patients with dysferlinopathy. However, the findings may be applicable to other slowly progressive forms of muscular dystrophy, which show periods of both deterioration and stability. Muscular dystrophies share a common pathomechanism of repeated cycles of muscle dam-

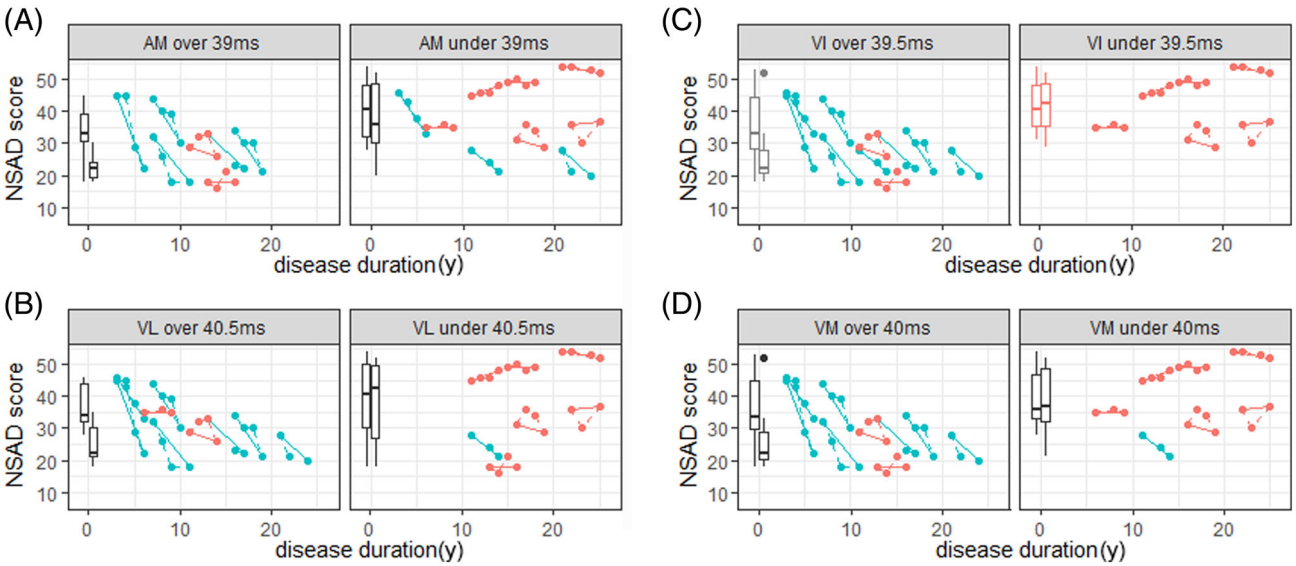

Figure 3 Disease progression in the cohort analysed, grouped by $T2_{H2O}$ threshold value identified for *(A)* adductor magnus (AM), *(B)* vastus intermedius (VI), *(C)* vastus lateralis (VL), and *(D)* vastus medialis (VM). Dots showing the North Star Ambulatory Assessment for Dysferlinopathy (NSAD) score at each time point are grouped by dashed lines to illustrate individual patient trajectories on the NSAD score over 3 years. Those deteriorating more than 5 points over 3 years are coloured blue, and those deteriorating 5 or less points are coloured red. Box plots represent the median, interquartile range, and range of NSAD score for patients at baseline (left) and Year 3 (right).

age and attempted repair, with release of pro-inflammatory cytokines and immune cell influx.[38–41] Such patterns of inflammation and oedema are detected by $T2_{H2O}$, suggesting that our finding may be extrapolated to other muscular dystrophies, although this needs to be confirmed in future studies.[29,37]

The results presented in this paper suggest that faster functional disease progression in dysferlinopathy can be predicted by higher $T2_{H2O}$ values in muscles of the thigh, over 1 and 3 years. With further research, we predict that similar patterns would be demonstrated in other slowly progressive forms of muscular dystrophy. However, it is important to take into account that an effort in standardizing the measurements between centres is crucial if these observations are to be employed in clinical trial design and prognostication for patients with muscular dystrophy.

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Conflict of interest

Ursula Moore, Ericky Caldas de Almeida Araujo, Harmen Reyngoudt, Heather Gordish-Dressman, Fiona E. Smith, Ian Wilson, Meredith James, Anna Mayhew, Jown W. Day, Kristi J. Jones, Diana X. Bhraucha Goebel, Emmanuelle Salort Campana, Alan Pestronk, Maggie Walter, Carmen Paradas, Tanya Stojkovic, Madoka Mori-Yoshimura, Elene Bravver, Elena Pegoraro, Jerry R. Mendel, Kate Bushby, Andrew M. Blamire, Volker Straub, Pierre Carlier, and Jordi Díaz-Manera have received funding for research from the Jain Foundation during the conduct of the study.

Laura Rufibach is hired by the Jain Foundation.

Online supplementary material

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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