Dysregulation of 4q35- and muscle-specific genes in fetuses with a short D4Z4 array linked to facio-scapulo-humeral dystrophy
Natacha Broucqsault, Julia Morere, Marie-Cécile Gaillard, Julie Dumonceaux, Julia Torrents, Emmanuelle Salort Campana, André Maues de Paula, Marc Bartoli, Carla Fernandez, Anne Chesnais, et al.

To cite this version:
Natacha Broucqsault, Julia Morere, Marie-Cécile Gaillard, Julie Dumonceaux, Julia Torrents, et al.. Dysregulation of 4q35- and muscle-specific genes in fetuses with a short D4Z4 array linked to facio-scapulo-humeral dystrophy. Human Molecular Genetics, Oxford University Press (OUP), 2013, 22 (20), pp.4206 - 4214. 10.1093/hmg/ddt272. hal-01662672

HAL Id: hal-01662672
https://hal-amu.archives-ouvertes.fr/hal-01662672
Submitted on 2 Jan 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Dysregulation of 4q35- and muscle-specific genes in fetuses with a short D4Z4 array linked to facio-scapulo-humeral dystrophy

Natacha Broucqsault1,†, Julia More1,†, Marie-Cécile Gaillard1, Julie Dumonceaux6, Julia Torrents2, Emmanuelle Salort-Campana1,3, André Maues De Paula1,2, Marc Bartoli1, Carla Fernandez2, Anne Laure Chesnais2, Maxime Ferreboeuf6, Laure Sarda2, Henry Dufour2, Claude Desnuelle7, Shahram Attarian1,4, Nicolas Levy1,5, Karine Nguyen1,5, Frédérique Magdinier1,7,∗ and Stéphane Roche1,†

1Aix Marseille Université, INSERM UMR_S910, 27 boulevard J. Moulin, 13005 Marseille, France, 2APHM, Laboratoire d’Anatomopathologie, 3APHM, Service de Neurochirurgie, 4APHM, Service de Neurologie, 5APHM, Laboratoire de génétique médicale, Hôpital de la Timone, 264 Rue Saint-Pierre, 13385 Marseille, France, 6UM76–UPMC, Inserm U974, CNRS UMR7215, 47, boulevard de l’Hôpital, La Pitié Salpêtrière-Bâtiment Babinski, 75651 Paris Cedex 13, France and 7Centre de Référence des Maladies Neuromusculaires, Nice University Hospital, 06000 Nice, France

Facio-scapulo-humeral dystrophy (FSHD) results from deletions in the subtelomeric macrosatellite D4Z4 array on the 4q35 region. Upregulation of the DUX4 retrogene from the last D4Z4 repeated unit is thought to underlie FSHD pathophysiology. However, no one knows what triggers muscle defect and when alteration arises. To gain further insights into the molecular mechanisms of the disease, we evaluated at the molecular level, the perturbation linked to the FSHD genotype with no a priori on disease onset, severity or penetrance and prior to any infiltration by fibrotic or adipose tissue in biopsies from fetuses carrying a short pathogenic D4Z4 array (n = 6) compared with fetuses with a non-pathogenic D4Z4 array (n = 21). By measuring expression of several muscle-specific markers and 4q35 genes including the DUX4 retrogene by an RT-PCR and western blotting, we observed a global dysregulation of genes involved in myogenesis including MYOD1 in samples with <11 D4Z4. The DUX4-fl pathogenic transcript was detected in FSHD biopsies but also in controls. Importantly, in FSHD fetuses, we mainly detected the non-spliced DUX4-fl isoform. In addition, several other genes clustered at the 4q35 locus are upregulated in FSHD fetuses. Our study is the first to examine fetuses carrying an FSHD-linked genotype and reveals an extensive dysregulation of several muscle-specific and 4q35 genes at early development stage at a distance from any muscle defect. Overall, our work suggests that even if FSHD is an adult-onset muscular dystrophy, the disease might also involve early molecular defects arising during myogenesis or early differentiation.

INTRODUCTION

Facio-scapulo-humeral dystrophy (FSHD) is an autosomal-dominant disorder, ranked as the most prevalent muscular dystrophy with an incidence of 7 of 100 000 (http://www.orpha.net). Symptoms usually arise between the age of 20–40. Clinically, the disease manifests predominantly as facial weakness with progression to the upper body and then to the lower extremities with a characteristic asymmetric involvement of certain groups of skeletal muscles. There is a marked inter-
and intra-familial heterogeneity in FSHD clinical expression, which probably depends on multiple genetic and environmental factors unknown yet. Importantly, FSHD is linked to deletion of an integral number of a 3.3 kb tandem macrosatellite repeat arranged as a head-to-tail array in the subtelomeric 4q35 region. Typically, non-affected individuals carry between 11-100 copies of this D4Z4 element while patients with FSHD present between 1-10 units. Distal to D4Z4, a region defines two allelic forms, 4qA and 4qB. The 4qA sequence is characterized by the presence of an array of the 68 bp β-satellite repetitive DNA and the pLAM sequence abutting the last D4Z4 repeat and containing a polyadenylation site (1,2). Both qA and qB alleles are equally common in the population but FSHD is associated with the 4qA allele (3). In unaffected individuals, long D4Z4 arrays harbor heterochromatin features, whereas FSHD-linked short D4Z4 arrays contain epigenetic marks of non-transcribed euchromatin (4–6). D4Z4, which contains >70% of CpG sites is hypermethylated at the DNA level in normal cells but hypomethylated in both 4q-linked (FSHD1) and phenotypic (FSHD2) FSHD.

So far, the search for a FSHD candidate gene has been controversial. The expression of several 4q35 genes has been determined in biopsies and primary myoblasts derived from patients, but their involvement and dysregulation in FSHD remain unclear with some authors observing a transcriptional deregulation of several of them (7–10) while other do not (11–13). Among the candidate genes for FSHD, the DUX4 retrogene localized within D4Z4 is suspected to play a key role (1,2,14,15). Each D4Z4 contains in its distal part an open reading frame encoding a putative protein containing two homeoboxes (1). In individuals carrying the 4qA allele downstream of the repeat, this DUX4 sequence can be transcribed through the last D4Z4 repeat and the proximal 4qA sequence leading to the production of a pre-messenger RNA with introns and a polyadenylation site (2,14,15). This pre-messenger RNA can be spliced into at least three different mRNAs of different sizes. In patient’s samples, full-length DUX4 transcripts (DUX4-fl) are detected at a very low level (in 1 of 1000 muscle cell nuclei) (15). In the current model, DUX4-fl might encode a toxic double homeobox transcription factor responsible for the activation of >500 other genes in skeletal muscle (16–18). Still, a major issue with the DUX4 hypothesis is its extremely low abundance, the difficulty to detect the protein in patient’s biopsies limiting its use as a biomarker for diagnosis or prognosis and the time window in which DUX4 becomes pathogenic.

Thus, the search for genes dysregulated in FSHD led so far to controversial conclusions and different reasons might explain these discrepancies. Furthermore, if the genetic defect is present constitutively in most of the FSHD cases, the clinical signs of the disease only appear late in life and nothing is known on the molecular features of the presymptomatic muscle, in particular during development. Therefore, we investigated whether biopsies from fetuses carrying a short D4Z4 array display a developmental-specific phenotype compared with normal samples and quantified the expression level of different muscle-specific and 4q35 genes, including DUX4. Collectively, our data reveal changes in expression of several muscle-specific genes in fetuses with a short D4Z4 array compared with normal specimen together with the dysregulation of several 4q35 genes, suggesting that muscle homeostasis is affected as early as the fetal stage in FSHD.

RESULTS AND DISCUSSION

Key questions with regard to FSHD is how and when the muscular phenotype arises, the identity of the gene(s) involved in the pathology and the link between D4Z4 and the regulation of the FSHD-causing gene(s) in specific muscles. Therefore, to evaluate at the molecular level the perturbation linked to the FSHD genotype with no a priori on disease onset, severity or penetrance and prior to any infiltration by fibrotic or adipose tissue, we explored the expression level of several muscle-specific genes during the second trimester of gestation in six fetuses carrying a short pathogenic D4Z4 array (FSHD carriers) compared with fetuses with a long non-pathogenic D4Z4 array (controls, n = 21) at different gestational ages by measuring the expression of (i) several muscle-specific genes, (ii) DUX4 and (iii) different 4q35 genes.

During the human intrauterine development, multinucleated primary myotubes appear around the 5th week of gestation, early muscle fibers around the 11th week while after the 20th week, most muscle fibers are packed with myofibrils and display peripheral nuclei similar to adult muscle. In fetuses, muscle mass increases predominantly by proliferative growth of myoblasts. Between the 20th and 24th weeks of gestation, innervation enhances muscle development and differentiation. Up to the 25th week, muscle displays a hyperplastic stage with an increase in cell number. Then, the cell size and muscle mass increase rapidly by hypertrophy while the postnatal growth of muscle is mostly characterized by remodeling of pre-existing fibers (19). Two types of muscle fibers are present during the fetal period, but the distinction cannot be made until the 18–20th week of gestation.

With regard to the developmental pattern of muscle-specific genes, our results in quadriceps indicate an increase in the expression of several genes encoding structural proteins such as sarcoglycan (7.7-fold), calpain 3 (4.4-fold), dysferlin (3.1-fold). Also upregulation of several genes encoding the myosin heavy chain was evidenced, either for genes corresponding to type I, slow oxidative red fibers (MYH1, 8.25-fold; MYH7, 3.75-fold) or type II, fast oxidative red fibers, MYH2 (56-fold) in FSHD fetuses (Fig. 1A; Supplementary Material, Table S3; at least 2-fold change in expression; P-value <0.05). Furthermore, a significant upregulation of genes encoding proteins involved in muscle remodeling (MURF1 (TRIM63), 5.3-fold) and calcium release was also observed at the RNA (RYR1-1, 10.7-fold; CACNA1S, 7.7-fold) and protein level (RYR1, 2.8-fold, Fig. 1B). Concerning transcription factors involved in muscle differentiation, both MYOD1 and MRF4 are upregulated in FSHD fetuses (6.8- and 21.4-fold, respectively, Fig. 1A; Supplementary Material, Table S3).

Using the same criteria, expression analysis was done on adult quadriceps biopsies from six non-carrier individuals and seven FSHD patients. Among the different genes mentioned above, only MYOD1 was found to be significantly upregulated (3.8-fold) in FSHD as described elsewhere (13) (Supplementary Material, Table S3, and Fig. S1). Interestingly, MMP9 expression usually modulated in dystrophic muscle is not modified in FSHD fetuses (Fig. 1A), but seems decreased in adult FSHD patients (Supplementary Material, Fig. S1).

The development and plasticity of striated muscle are due to finely tuned networks acting at different levels from the prenatal...
to the post-natal period. Aberrant transcription of genes involved in the proliferation or differentiation of muscle cells is usually associated with intrinsic muscle defect. Histological observation of affected muscle from FSHD patients did not reveal any specific pathological change except, in some cases, changes in the fiber size, presence of angular fibers, infiltration by adipocytes, replacement of muscle fibers by fibrotic and inflammatory tissues or subtle sarcolemmal reorganization, which might change force generation by type II fibers (20,21). Also, from earlier work on primary cultures, necrotic features have been described for FSHD myoblasts, which are more sensitive to stress, while FSHD myocytes fuse at a faster rate compared with controls but retain the appearance of an undifferentiated state. We report here, for the first time, global molecular changes in the fetal myogenic differentiation program, prior to any sign of dystrophic phenotype, suggesting that subtle molecular changes precede the dystrophic phenotype. Our work suggests that the clinical FSHD-specific phenotype might find its origin at very early developmental stages prior to any clinical sign of the disease. As suggested by others, even if FSHD is an

Figure 1. Transcriptional analysis of muscle-specific genes in fetal and adult muscle. (A) The box plots correspond to GUSB normalized data. P-values are indicated in each box. Experiments were done in triplicate. Horizontal lines are medians, the boxes correspond to the 50th percentile and the whiskers to the 75th percentile. Normalized transcription and P-values are given in Supplementary Material, Table S2. (B) Immunodetection of the RYR1 protein by western blotting (upper panel). Detection of Lamins A/C western was used as a reference (lower panel). The left panel corresponds to the quantification by densitometry of the RYR1/Lamins A/C signals. Boxes correspond to the 25th percentile and the whiskers to the 75th percentile. Horizontal lines correspond to the median.
adult-onset muscular dystrophy, the disease might also depend on defects during myogenesis or early differentiation. Type-I slow-twitch oxidative fibers are preferentially found at early developmental stages, while type-II (fast twitch glycolytic) increases after the 26th week (22,23). Then, developmental myosin isoforms are progressively replaced by the adult isoforms. The marked increase in MYH2 in FSHD fetuses compared with controls suggests either modification in fiber conversion as observed in adults affected with FSHD (20,24) or a change in the timing of replacement since the change from type I to type II is usually seen after the 26th week of gestation. Furthermore, in FSHD, the presence of immature fibers expressing fetal myosin has been observed (25,26), suggesting also that maintenance or reactivation in the post-natal or adult muscle of factors acting during the intrauterine period might contribute to the cascade of alterations leading to the pathology.

The identity of the gene(s) involved in the pathology remains a matter of debate, but ectopic expression of the DUX4 retrogene from the last D4Z4 repeat and the distal qA region has been proposed as the main cause of the FSHD phenotype (1,2,15,16). To address whether DUX4 was present at early developmental stages, we used oligoiT primed complementary DNA (cDNA) and PCR amplification with the primers previously described (15) to determine the presence of the full-length DUX4 transcript (DUX4-fl), blindly to the genetic background, in different fetal muscles from 5 FSHD fetuses and 21 controls (Fig. 2A, Table 1), but also in other tissues normally not affected in FSHD (diaphragm, spinal cord, skin, brain, and kidney). We detected the DUX4-fl mRNA in four of five FSHD samples either in biceps (one of four tested) or quadriceps (four of four) (Table 1), but also in non-affected somatic tissues such as skin, brain or kidney (Supplementary Material, Table S4), confirming that DUX4 transcription can be observed in tissues (muscular and non-muscular) from individuals carrying a shortened D4Z4 array as observed in muscular biopsies from adult FSHD patients (15). Moreover, as observed in healthy adult muscle (27), we also report the presence of the DUX4-fl in fetal biopsies from genetically unaffected fetuses although at a lower frequency (in 5 out of 17 biceps and 5 out of 21 quadriceps tested, Table 1), but also in non-muscular samples, not affected in the disease (Supplementary Material, Table S4). In adult samples, we confirmed the presence of the DUX4-fl in quadriceps of both controls (three of six) and FSHD patients (three of seven).

In FSHD patients carrying the 4qA allele downstream of the repeat, the transcription of DUX4 through D4Z4 and the proximal 4qA sequence produces a pre-messenger RNA with introns (1,2,15) spliced into different mRNAs varying in size and containing a polyadenylation site. A short DUX4 transcript (DUX4-s) can be detected in myoblasts from patients and 50% of controls. The long DUX4 transcript (DUX4-fl) is detected at a very low level (in 1 of 1000 muscle nuclei) in 50% of FSHD patient’s biopsies, 40% expressing the DUX4-s and the others 10% presenting no expression of either form (15), but also in primary myoblasts and muscle biopsies from non-carrier unaffected adults (27).

In order to confirm specificity and sequence, we sequenced all PCR products amplified with the DUX4-fl primers and observed striking differences in splicing between FSHD carriers and controls. In most of the DUX4-positive samples from FSHD carriers (four out of five), we amplified the non-spliced DUX4-fl isoform, while eight out of nine controls express the spliced DUX4-fl. Indeed, two alternative forms have been described for the DUX4-fl pathogenic transcripts differing by alternative splicing of a 135 bp-long intron in the 3’ UTR (Fig. 2B). The termination codon of the DUX4 protein is located before the first alternative intron, and splicing is not expected to modify the frame or sequence of the pathogenic DUX4 protein. Our data on DUX4 are consistent with the recent report showing the prevalence of a long DUX4-fl transcript in approximately half of the FSHD biopsies tested (15), but also in unaffected individuals (27). However, we extend here these findings by demonstrating that (i) DUX4 is expressed as early as fetal development, together with DUX4 targets (Ferrebouef et al., submitted), in muscular and also non-muscular somatic tissues; (ii) both spliced and non-spliced DUX4-fl isoforms are found in adult muscle (iii) in fetal FSHD samples, RNA processing of the first intron is rarely observed, suggesting a FSHD-specific control of splicing. However, after their initial description (2,14,15), the respective regulation, the presence or role of the two variants has not been further investigated or discussed, and recent reports focusing on the biological function of the DUX4 protein describe a DUX4-fl encoding vector without any precision on whether it corresponds to the spliced or non-spliced form. After cloning of the PCR products and sequencing, we did not observe any co-expression of the spliced or non-spliced DUX4-fl suggesting that, as observed for DUX4-s and DUX4-fl, the two isoforms might be mutually exclusive. Nevertheless, the underlying mechanisms regulating alternative splicing and their respective role remain to be investigated.

Based on the hypothesis of a position effect mechanism, gradual changes in the expression of genes located at the 4q35 locus have been proposed for FSHD. In this model, relaxation and long-range chromatin-dependent mechanisms might be associated with increased and variable expression of one to several genes at distance of the D4Z4 array. So far, upregulation of the 4q35 genes has been a matter of debate with some authors showing an increase in expression of several of them (8–10) and others disputing these findings (11–13) in the absence of a gradient correlating distance from D4Z4 and gene expression (11,12,28). The reasons for such discrepancies are not known, but might depend on the type of sample (biopsies versus primary myoblasts or myotubes), type of muscle but also inter-individual variability linked to genetic or epigenetic factors. To limit the impact of such variability and elucidate the regulation of the 4q35 genes in individuals carrying a short D4Z4 array, we selected 36 genes located in the 4q35 region and measured their expression at the RNA level in muscular biopsies from 6 FSHD and 21 control fetuses. For at least 14 of the 4q35 genes, a significant increase in expression was observed in quadriceps (Fig. 2C; Supplementary Material, Table S4; at least 2-fold change in expression; P-value <0.05). We were not able to detect FRG2 transcripts in fetal biopsies, but observed FRG1 (10.9-fold; P < 0.04) and SLC25A4 (ANT1, 6-fold, P < 0.005) upregulation. In addition, the PDLIM3 gene (2.17-fold) involved in skeletal muscle function is also upregulated in FSHD fetuses. In adults, upregulation of ANTI has already been reported (8,29) and proposed as an early event in the pathological process (9), while no noticeable changes were reported for PDLIM3 (ALP) (12,30) involved in Z-disc organization and regulation of the myogenic differentiation transcriptional network(31). Distal to
Figure 2. Expression of the 4q35 genes in fetal samples. (A). Upper panel, gel showing PCR products obtained after reverse transcription and nested PCR amplification on RNA extracted from muscle biopsies (biceps and quadriceps) and other somatic tissues of fetuses carrying a short D4Z4 array (FSHD1-7UR-6; FSHD1-2UR-1) or non-carriers (F-CT16). Lower panel corresponds to amplification from samples not treated with reverse transcriptase (RT) (B). Schematic representation of the last D4Z4 repeat encoding the two DUX4-fl isoforms. The DUX4 exons indicated have grey boxes and numbered (1–3). The position of the polyadenylation site (PAS), stop codon (star) and primers used for RT–PCR are indicated. (C). Diagram showing changes in gene expression across the 4q35 region in quadriceps from fetuses (n = 6; upper panel) and adults (n = 7; lower panel) carrying a shortened D4Z4 array compared with controls (fetuses, n = 21; adults, n = 6). Black and upper cases: upregulated genes; Grey upper case: downregulated genes; black: no significant change; grey, not expressed. Experiments were done in triplicate. Normalized
**Table 1. Amplification of the DUX4-fl isofom in fetal and adult muscles**

<table>
<thead>
<tr>
<th>Gestational age (weeks)</th>
<th>Biceps</th>
<th>Quad.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fetuses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FSHD1-2UR-1</td>
<td>16</td>
<td>(+)²</td>
</tr>
<tr>
<td>FSHD1-4UR-2</td>
<td>16</td>
<td>(+)²</td>
</tr>
<tr>
<td>FSHD1-2UR-4</td>
<td>25</td>
<td>N.A.</td>
</tr>
<tr>
<td>FSHD1-7UR-5</td>
<td>26</td>
<td>N.A.</td>
</tr>
<tr>
<td>FSHD1-7UR-6</td>
<td>26</td>
<td>(+)²</td>
</tr>
<tr>
<td>F-CT1</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>F-CT3</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>F-CT3</td>
<td>14</td>
<td>(+)¹</td>
</tr>
<tr>
<td>F-CT4</td>
<td>14</td>
<td>(+)¹</td>
</tr>
<tr>
<td>F-CT5</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>F-CT6</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>F-CT7</td>
<td>15</td>
<td>(+)¹</td>
</tr>
<tr>
<td>F-CT8</td>
<td>18</td>
<td>N.A.</td>
</tr>
<tr>
<td>F-CT9</td>
<td>18</td>
<td>(+)¹</td>
</tr>
<tr>
<td>F-CT10</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>F-CT11</td>
<td>21</td>
<td>N.A.</td>
</tr>
<tr>
<td>F-CT12</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>F-CT13</td>
<td>24</td>
<td>N.A.</td>
</tr>
<tr>
<td>F-CT14</td>
<td>25</td>
<td>(+)¹</td>
</tr>
<tr>
<td>F-CT15</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>F-CT16</td>
<td>26</td>
<td>(+)²</td>
</tr>
<tr>
<td>F-CT17</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>F-CT18</td>
<td>37</td>
<td>(+)²</td>
</tr>
<tr>
<td>F-CT19</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>F-CT20</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>F-CT21</td>
<td>37</td>
<td></td>
</tr>
</tbody>
</table>

Age at enrollment (yrs) | Biceps | Quad. |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Adults</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-CT1</td>
<td>16</td>
<td>N.A.</td>
</tr>
<tr>
<td>A-CT2</td>
<td>16</td>
<td>N.A.</td>
</tr>
<tr>
<td>A-CT3</td>
<td>60</td>
<td>(+)¹</td>
</tr>
<tr>
<td>A-CT4</td>
<td>45</td>
<td>(+)¹</td>
</tr>
<tr>
<td>A-CT5</td>
<td>49</td>
<td>(+)¹</td>
</tr>
<tr>
<td>A-CT6</td>
<td>52</td>
<td>N.A.</td>
</tr>
<tr>
<td>FSHD1-1</td>
<td>54</td>
<td>N.A.</td>
</tr>
<tr>
<td>FSHD1-2</td>
<td>66</td>
<td>N.A.</td>
</tr>
<tr>
<td>FSHD1-3</td>
<td>61</td>
<td>N.A.</td>
</tr>
<tr>
<td>FSHD1-4</td>
<td>61</td>
<td>N.A.</td>
</tr>
<tr>
<td>FSHD1-5</td>
<td>57</td>
<td>N.A.</td>
</tr>
<tr>
<td>FSHD1-6</td>
<td>57</td>
<td>(+)¹</td>
</tr>
<tr>
<td>FSHD1-7</td>
<td>45</td>
<td>N.A.</td>
</tr>
</tbody>
</table>

The table recapitulates the results of at least three independent experiments. Samples positive in at least two out of the three RT–PCR assays have been sequenced. (−) indicates that the DUX4-fl transcript was not detected. (+) corresponds to samples where DUX4-fl was detected (either biceps or quadriceps). Each amplicon was sequenced and presence of either the spliced (+) or non-spliced (−) DUX4-fl isofom is indicated.

**PDLIM3, the SORBS2 gene regulated by the PDLIM3-SORBS2 distal enhancer (32)** during muscle development is not differentially expressed in FSHD (Fig. 2C, Supplementary Material, Fig. S4). In the vicinity of PDLIM3A and SCL25A4, four other genes are upregulated (LRP2BP, ACSL1, ANKRD37 and UFSP2). LRP2BP (6.11-fold) regulates LRP2 function and HDL endocytosis and ACSL1 (4.3-fold) encodes the acyl-coenzyme A synthetase long chain 1 implicated in the adaptation of several tissues including muscle to aerobic metabolism. The function of ANKRD37 is not known, but might be activated by HIF1 in response to hypoxia while UFSP2 encodes an ubiquitin-field modifier protease. Their respective function in muscle remains obscure. Two additional genes are also upregulated in FSHD: MNTR1A (5.43-fold) encoding a melatonin receptor and ING2 (2.12-fold) encoding a chromatin-remodeling factor implicated in muscle differentiation. Beside DUX4C (7.3-fold, P < 0.05), two genes ENPP6 (ectonucleotide pyrophosphatase/phosphodiesterase 6), WWC2 (WW and C2 domain containing protein) appear to be slightly down-regulated in FSHD compared with control muscles (2.3-: -1.9- respectively, P > 0.05; Figure 2C; Supplementary Material, Table S5, Supplementary Material, Fig. S2C). SCL25A4 and WWC2 were immunodetected by western blotting and densitometry analysis confirmed their respective up- (29.6-fold, P < 0.1; Fig. 2D) or down-regulation (3.5-fold; P < 0.1; Fig. 2E) in fetal quadriceps FSHD samples compared with age-matched controls. As a comparison, we examined the expression status of the 36 genes in seven FSHD adult biopsies and six controls (Supplementary Material, Fig. S2 and Table S5). In agreement with the literature but in contrast to fetuses, we did not observe any significant dysregulation for these genes in adult muscles.

In fetuses, shortening of the D4Z4 array is accompanied with dysregulation in a set of genes involved in myogenesis suggesting an altered myogenesis as early as the fetal stage. The genetic defect linked to FSHD might directly or indirectly disrupt the myogenic program as discussed before (33). Wasting and weakening in adult FSHD muscle might thus result from the long-term accumulation of defects such as structural changes, fiber conversion or response to stress arising as early as the fetal life. In FSHD, the rationale for the selective and asymmetrical involvement of specific groups of muscle remains unclear, since all the affected muscle do not originate from the same somite or same region in the embryo. However, one can speculate that common regulatory pathways regulating migration or differentiation of muscle cells are affected during muscle differentiation, and that the abnormality leading to the pathology begins during development. Strikingly, many of the 4q35 genes upregulated in muscles of FSHD carriers are also implicated at different levels in muscle function and homeostasis. Thus, dysregulation of the 4q35 locus together with changes in muscle-specific genes might alter the capacity of the muscle fiber to respond to stress during adult life leading, in turn, to the progressive weakening observed at the clinical level. We did not find any evidence of a common regulatory pathway for the different genes upregulated in FSHD fetuses (Supplementary Material, Figure S3) but, interestingly, many of the genes strongly upregulated in fetuses (ACSL1, LRP2BP, PDLIM3, SLC25A4, UFSP2 and MNTR1A) are clustered in a region located ∼5–5.5 Mb upstream of the most proximal D4Z4 element, flanked by two genomic regions located to the nuclear periphery (lamin attachment domains). This observation, in light of our previous work (4,34,35) and data from others (36,37), suggests that transcription values are indicated in Supplementary Material, Table S6. We also observed upregulation of PDLIM3, UFSP2, STOX2, ING2, ANTI in biceps from FSHD fetuses. The corresponding box plots are shown in Supplementary Material, Figure S5. Upregulation is not correlated either with orientation of the gene or with the presence of a CpG island at the promoter region. (D) Western blot of ANTI/SCL25A4 and (E) WW2 protein. Lamins A/C were used as a reference. On the left of each gel, quantification by densitometry of the protein-specific band/Lamins A/C signals. Horizontal lines are medians, the boxes correspond to the 25th percentile and the whiskers to the 75th percentile.
conformational and topological changes mediated by D4Z4 array shortening might modify the regulation of the whole 4q35 region. Furthermore, with regard to expression of the 4q35 genes and muscle-specific genes, our results suggest that FSHD might not simply result from overexpression of a single gene or retrogene, but more likely from a cascade of dysregulations at different stages of the muscle development and maturation associated with the DUX4-dependent cascade or on other D4Z4-dependent modification.

At this step, it remains difficult to connect into a single model the mechanism of the disease and the respective contribution of the different DUX4-fl isoforms and other genes in the pathogenesis of this complex muscular dystrophy. Transcriptional mechanisms governing D4Z4 transcriptions are likely to be important for understanding the pathology since a large number of small, polyadenylated or long non-coding RNA emanating from the repeat have been described (14,38,39). In general, our data suggest that reduction in the number of D4Z4 might lead to the pathology by enhancing in cis expression of different genes including DUX4. However, the absence of the pathogenic DUX4-fl in a number of FSHD cases (15), its presence non-muscular somatic tissues in FSHD carriers but also in unaffected individuals (27) suggest that other alterations or pathways might contribute to the muscular phenotype as a direct or indirect consequence of this cis effect. FSHD is a highly variable disease with a high variability in penetrance within families even in individuals carrying the same number of repeats or monozygotic twins (25,40,41), suggesting that environment and lifestyle modify expression of the gene(s) involved in the disease. Overall, our work does not exclude a role for a stable DUX4 transcript linked to a short or relaxed D4Z4 array and the presence of a distal functional polyadenylation site, but suggests that DUX4 detection is not the only marker of FSHD. Disease onset and progression might be associated with either dosage of the pathogenic transcript, stability or maintenance in the muscle fiber or burst of activation at critical stages. Of note, we were able to detect DUX4 as early as the 14th week of gestation in normal fetuses and 16th week in FSHD samples, corresponding to the formation of fibers and myofibrils (11–20th week). Recent data indicate that DUX4 is regulated during embryogenesis (42), and that muscle is sensitive to DUX4 dosage at very early stages (43). Hence, the window of time in which DUX4 is activated might be critical for FSHD. However, dysregulation of different 4q35 and muscle-specific genes in fetal muscles also suggests that a cascade of events probably precedes FSHD symptoms, and that accumulation of defects at different stages of muscle development might contribute to the pathomechanisms.

Quantitative RT–PCR

Total RNA was extracted from biopsies using the classical Chomczynski and Sacchi method (44). Reverse transcription of 1 μg of total RNA was performed using the Superscript II kit and oligo dT following manufacturer’s instructions at 42°C for 50 min followed by inactivation at 70°C for 15 min (Life Technologies). Primers were designed using Primer Blast and Primer 3 (Supplementary Material, Table S1). Real-time PCR amplification was performed on a LightCycler 480 (Roche) using the SYBR green master mix. All PCRs were performed using a standardized protocol, and data were analyzed with the Lightcycler 480 software version 1.5.0.39 (Roche). Primer efficiency was determined by absolute quantification using a standard curve. For each sample, fold change was obtained by comparative quantification and normalization to expression of the GUSB standard gene. Similar results were obtained after normalization to β-actin or β2M. For statistical analysis, data are expressed as means ± SEM. Statistical significance was assessed by the non-parametric Wilcoxon–Mann–Whitney statistical test using the Gnemonic spreadsheet version 1.10.16.

RT–PCR for DUX4

One microgram of total RNA was used for first-strand cDNA synthesis using SuperScript II reverse transcriptase and oligo dT as described above. Primary PCRs were performed with Taq DNA polymerase (Euromedex) using 7% of the first-strand reaction as template in a total reaction volume of 30 μl. Nested PCRs were performed on 1 μl of the primary reaction. For DUX4-fl detection, the following primers were used: PCR1-forward: 5′-CCC CGA GCC AAA GCG AGG CCC TGC GAG CCT-3′; PCR1-reverse: 5′-GTA ACT CTA ATC CAG GTT TGC CTA GA-3′; PCR2-forward: 5′-CCG CCC TGG CCC GGG AGA ACG CCG CCC GC-3′; PCR2-reverse 5′-CTC AAT CCA GGT TTG CCT AGA GAV C C3′ as described in (15). PCR products were examined on 3% Molecular Biology Grade Agarose gels stained with ethidium bromide. In order to discard any risk of contamination by genomic DNA, each RNA sample was treated with DNase I and PCR amplification was performed on RNA samples incubated in the absence of reverse transcriptase (RT-) or without addition of cDNA. In all cases, amplification products were only observed when RNA samples were reverse-transcribed. All PCR products were sequenced.

MATERIALS AND METHODS

Biological samples

Fetal biopsies from FSHD (n = 6) and non-carrier fetuses (n = 21) were obtained after therapeutic abortion. Research was approved by the biomedicine agency (PFS13-006). The parents have provided written informed consent for the use of biopsies for medical research in accordance with the Declaration of Helsinki. Controls are neither carrier of any known genetic mutation nor affected by a muscular pathology. Adults have provided informed consent and muscles of clinically affected and control individuals were obtained using a standardized muscle biopsy protocol. Controls were selected in the same age range and sex representation.

Western blot

Whole protein extracts were obtained from biopsies disrupted in 200 μl extraction buffer (Tris-HCl pH 8 100 mm, 10% SDS, 10 mM EDTA, 10% glycerol, protease inhibitor) using a T18 Ultra Turax. Proteins were separated by electrophoresis and transferred onto a PVDF membrane following the protocol recommended by the supplier for the Life Technologies NuPAGE system (including MOPS running buffers, Bis/Tris 4-12% gels and NuPAGE transfer buffer). PVDF membranes
were blocked for 1 h in 5% (w/v) non-fat dry milk in PBS-Tween (0.1% Tween-20 in PBS) and incubated for 90 min with the following primary antibodies: Lamin A/C (1 of 10 000, Clone 4C11, Sigma-Aldrich), WWC2 (1 of 1000, Sigma-Aldrich), SLC25A4 (1 of 1000, Sigma-Aldrich), RYR1 (1 of 1000, ref: ab2868, Abcam). After four washes in PBS-T, an anti-mouse IgG secondary antibody coupled to horseradish peroxidase (ThermoFisher) was incubated for 90 min (1/20 000). After washes, the signal was revealed by enhanced chemiluminescence (ECL, SuperSignal West Pico, Pierce) using a biospectrum imaging system (UVP).

ACKNOWLEDGMENTS

We are indebted to all families for participating in this study. We wish to thank Mr Armand Tasmadjian for technical help. We also thank Dr Sabrina Sacconi for providing adult biopsies and critical reading.

Conflict of Interest statement. N.B. is the recipient of a fellowship from AFM (Association Francaise contre les Myopathies). S.R. is the recipient of a fellowship from ANR (FSHDecrypt, ANR-09-GENO-038), M.-C.G. is the recipient of a fellowship from the FSH Society and M.F. is the recipient of a fellowship from FSHD Global (Australia).

FUNDING

This study was funded by FSHD Global (Australia), the FSH Society (USA) and an ANR grant (FSHDecrypt, ANR-09-GENO-038) (to F.M.).

REFERENCES

Gene. 236, 25–32.
Science. 329, 1650–1653.
Am. J. Hum. Genet. 75, 1124–1130.
PloS Genet., 5, e1000394.
Cell. 110, 339–348.
PloS One, 6, e20966.
PloS Genet., 6, e1001181.
PloS One, 6, e26820.
Ann. Neurol. 69, 540–552.


