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Molecular Mechanisms of FSH Muscular Dystrophy Pathogenesis

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Molecular mechanisms of FSH muscular dystrophy pathogenesis

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Facioscapulohumeral Muscular Dystrophy (FSHD)

Most prevalent muscular dystrophy afflicting children and adults (~1:7,000-15,000)

**Autosomal dominant**

- **Facio:** refers to face
- **Scapulo:** refers to shoulders
- **Humeral:** refers to humerus (upper arm bone)

Winging on both sides in a patient with FSHD due to weakness of all the scapula stabilizing muscles

Great genetic and clinical heterogeneity
Each patient may differ in severity
Most patients exhibit symptoms by age 20
>50% of patients retain ability to walk
The FSHD1 genetic lesion is a deletion in a tandem repeat array at 4q35

Human chromosome 4q35, Normal D4Z4 n=11-150

Human chromosome 4q35, D4Z4 contraction 1<N<11

FSHD
A pathogenic FSHD1 deletion is complex

- The deletion itself is not pathogenic
- The 4qA sub-telomere is permissive, not pathogenic
- The 4qB sub-telomere is not permissive
- Requires at least 1 D4Z4 repeat unit for FSHD
- Chromosome 10 arrays (devoid of chr. 4 D4Z4) are not linked to FSHD
A putatively pathogenic FSHD1 deletion shows very low penetrance

Normal

Unaffected

FSHD1A

The deletion itself is not pathogenic
The 4qA sub-telomere is permissive, not pathogenic


~1:7-14,000

~1% of population
FSHD2 is independent of the contraction

The 4qA sub-telomere is required for FSHD1 and 2
At least 1 D4Z4 is required for FSHD1 and 2
FSHD is linked to D4Z4, the A type subtelomere and the epigenetic status of the 4q35 D4Z4 repeat.

Normal

FSHD1

FSHD2

\(\bullet\) = Hypermethylated CpGs more heterochromatic

\(\bigcirc\) = Hypomethylated CpGs more euchromatic
The 3 types of FSHD are linked by epigenetic dysregulation

FSHD1: Dominant deletions at 4q35 D4Z4 array
   Apparently low penetrance
   **DNA Hypomethylation** of shortened 4q35

FSHD2: SMCHD1 inactivating mutations
   --ATPase chromatin remodeling protein
   --Modifier of metastable epialleles
   **DNA Hypomethylation** of 4q35 and 10q26 arrays

IFSHD: Infantile form of FSHD1 or FSHD2, much more severe
   **DNA Hypomethylation** of FSHD1 or 2
FSHD is linked to the A type subtelomere and the epigenetic status of the 4q35 D4Z4 repeat

Normal

FSHD1

FSHD2

= Hypermethylated CpGs
more heterochromatic

= Hypomethylated CpGs
more euchromatic
FSHD results from an epigenetic-mediated dysregulation of gene repression

- DNA methylation
- Histone modifications
- Chromatin structure
- Long non-coding RNAs
- Nuclear organization
- High variability within the clinical population
  - Severity
  - Age of onset
  - Gene expression
*Which gene(s) is responsible for FSHD pathology?*

**The FSHD causal gene:**
1. Should be misexpressed in FSHD (Up or down)
   - mRNA, protein, cell type, developmental timing
   - adversely affect skeletal muscle and potentially vasculature

2. Explain the 4qA linkage and under epigenetic repression

Both FRG1 and DUX4 produce phenotypes consistent with FSHD when overexpressed in animal models
Wellstone family cohorts of muscle biopsies and myogenic cell cultures

Subjects screened for FSHD clinically and genetically

Genotyping (Iowa Wellstone) → Cell Culture (UMMS)

Biopsies (KKI-JHU) → mRNA & protein analysis (CHB, UMMS)

Microsatellite analysis (CHB)

Deltoid – Expect less pathology
Biceps – Expect more pathology

FSHD1 affected and genetically unaffected 1st degree relatives
Myogenic cultures from FSHD and unaffected first-degree relatives have similar patterns of gene expression during proliferation and myogenic differentiation.

Normalization genes

FSHD Candidate genes

Homma et al. (2012) EJHG
“A Unifying Model for FSHD” based on DUX4

FSHD permissive 4qA subtelomeres encode a third exon containing a polyadenylation site that stabilizes the DUX4 mRNA

Chr 4qB or Chr 10qA or 10qB → Normal

- Unstable mRNA
- DUX4 protein not made
- Nontoxic

Chr 4qA → FSHD

- Stable poly A mRNA
- DUX4 protein produced
- DUX4 expression is exclusive to FSHD

PAS = polyadenylation site
NP = non-permissive
P = permissive

PAS = polyadenylation site
* = translation stop

Lemmers et al. (2010) Science 329:1650
FSHD permissive 4qA subtelomeres encode a third exon containing a polyadenylation site that stabilizes the DUX4 mRNA.

Chr 4qB or Chr 10qA or 10qB → Normal
- Unstable mRNA
- DUX4 protein not made
- Nontoxic

Chr 4qA → FSHD
- Stable poly A mRNA
- DUX4 protein produced
- DUX4 expression is exclusive to FSHD

Lemmers et al. (2010) Science 329:1650
DUX4-FL expression leads to massive loss of developing myogenic cells

Xenopus embryos

1 pg DUX4-fl mRNA

Immunostaining for developing skeletal muscle

Wuebbles et al. (2010) *IJCEP*
DUX4-fl mRNA is expressed in FSHD1-derived myogenic cells

DUX4-fl mRNA expression is not exclusive to FSHD1-derived myogenic cells

DUX4-fl mRNA expression is expressed in both FSHD1-derived and unaffected muscle biopsies

Differentiated myogenic cells from genetically FSHD1 and control subjects express DUX4-FL protein

DUX4-FL expression in myogenic cells from FSHD affected unaffected subjects suggests a quantitative model of pathogenesis

FSHD is linked to the permissive 4qA subtelomere, the epigenetic status of the 4q35 D4Z4 repeat and DUX4-fl expression

Normal

FSHD1

FSHD2

= Hypermethylated CpGs more heterochromatic

= Hypomethylated CpGs more euchromatic
Which gene(s) is responsible for FSHD pathology?

The FSHD causal gene:
1. Should be misexpressed in FSHD (Up or down)  
   → mRNA, protein, cell type, developmental timing  
   → adversely affect skeletal muscle and potentially vasculature

2. Explain the 4qA linkage and under epigenetic repression

DUX4 fulfills these criteria
Many DUX4-FL responsive genes are upregulated in FSHD myotubes (biomarkers)

Oliver King, et al. (2012)
Increased DUX4-fl expression appears necessary* but alone is not sufficient for FSHD
FSHD-derived myoblasts are epigenetically poised to express DUX4-fl.

Decitabine treatment leads to DNA demethylation.
FSHD derived myogenic cells are epigenetically poised to express DUX4-fl mRNA

**Graph:**
- X-axis: 5-ADC, TSA, 17Abic, 17Ubic
- Y-axis: Normalized Fold Expression
- Comparison of treatments:
  - 5-ADC: - 5µM 1µM 5µM -
  - TSA: - - + + - - 5µM 5µM -
  - 17Abic: - + + +
  - 17Ubic: - - + +

**Conclusion:**
- DUX4-fl qRT-PCR Analysis
FSHD subjects show individual variability in the stability of DUX4-fl epigenetic repression
The 4q35 D4Z4 in FSHD exists as differentially metastable epialleles among affected subjects → epigenetically poised for DUX4 expression

The 4q35 D4Z4 in normal subjects exhibits stable epigenetic repression
Differentiated myogenic cells from genetically FSHD1 but clinically non-manifesting subjects express DUX4-FL protein.

Clinically FSHD

- 15Abic
- 28Adel
- 29Abic
- 29Adel

Clinically Non-manifesting

- 15Bbic
- 28Bdel
- 29Bbic
- 29Bdel

Non-manifesting

- 15B = 69 yr old
- 28B = 68 yr old
- 29B = 70 yr old

Affected

- 15A = 66 yr old
- 28A = 44 yr old
- 29A = 39 yr old

T. Jones et al. (2012)
DUX4-FL expression in myogenic cells from FSHD1 subjects that show no clinical manifestation of the disease suggests modifiers of disease

D. Jones et al. (2012)
DUX4 expression alone is not necessarily causal for FSHD

Normal

FSHD1

FSHD2

= Hypermethylated CpGs more heterochromatic

= Hypomethylated CpGs more euchromatic
Multiple therapeutic targets for FSHD

1. Prevent induction

Upstream regulators
- Induction of DUX4-fl
- Environmental factors
- Family background
- Genetic modifiers

2. Knockdown DUX4-fl

3. Block or reduce pathogenic drivers

Downstream effectors
- Inflammatory response
- Cytotoxicity
- Gene regulation
- Genetic modifiers

Pathogenic cascade
Multiple therapeutic targets for FSHD

**Upstream regulators**
- Induction of DUX4-fl
- Environmental factors
- Family background
- Genetic modifiers

**Downstream effectors**
- Inflammatory response
- Cytotoxicity
- Gene regulation
- Genetic modifiers

**Key to therapy may lie with identifying the disease modifiers**

1. Prevent induction
2. Knockdown DUX4-fl
3. Block or reduce pathogenic drivers
Analysis of DUX4 mRNA and protein expression in muscles and myogenic cells from FSHD subjects and unaffected relatives

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NIAMS
National Institute of Arthritis and Musculoskeletal and Skin Diseases

MDA
Muscular Dystrophy Association

AFM
Association Française contre les Myopathies