WORLD JOURNAL OF PHARMACEUTICAL RESEARCH
Coden USA: WJPRAP Impact Factor 8.63
Volume 15, Issue 22, 424-439. Review Article ISSN 2277–7105

A REVIEW ON NANOPARTICLE THERAPEUTICS IN FSHD: CURRENT RESEARCH AND FUTURE PERSPECTIVES

B. Indravathi[1], Prasanna Kumar Desu[1], B. Srinidhi[1], K. Harshitha[1*]

*[1]Department of Pharmaceutics, Dr. Samuel George Institute of Pharmaceutical Sciences, Markapur, Andhra Pradesh, India.

Article Received on 15 Oct. 2026,
Article Revised on 05 Nov. 2026,
Article Published on 16 Nov. 2026,

https://doi.org/10.5281/zenodo.24272892

***Corresponding Author**

K. Harshitha

Department of Pharmaceutics, Dr. Samuel George Institute of Pharmaceutical sciences, Markapur, Andhra Pradesh, India.

How to cite this Article: B. Indravathi[1], Prasanna Kumar Desu[1], B. Srinidhi[1], K. Harshitha[1*] (2026). A Review On Nanoparticle Therapeutics In Fshd: Current Research And Future Perspectives. World Journal of Pharmaceutical Research, 15(22), 424–439

This work is licensed under Creative Commons Attribution 4.0 International license.

ABSTRACT

Facioscapulohumeral muscular dystrophy (FSHD) is a genetic neuromuscular disease demonstrated by developing, asymmetric muscularimpairmentinduced by abnormal expression of the DUX4 (double homeobox 4) gene regulatory protein. There are presently no disease-altering therapiesprovided, and treatment accessibleendureregulated to assistive and indicativeapproachesthoughdevelopments in awareness of its molecular basis. Attempts have been meant to create treatmentmethods addressing DUX4 suppressing, genomicmodifying, and subsequent pathological mechanismschanging to consider its pendingclinical requirements. Clinical implementation is yethindered by the scarcity of efficient, organ-specific delivery to skeletal muscle. Nanotechnology-based vectors are potential for addressing these barriers, as they enhance tissue identifying while limiting off-target allocation and therapeutic drug content. In this review, we examine the existingscenario of FSHD treatments and emphasises how preclinical statistics on nanotherapeutics in Duchenne muscular dystrophy and variable muscular dystrophies illustrate the feasibility of nanoparticle-facilitatedtactics for muscle-targeted delivery and upgradeddrug availability in circulation, developingthese advancing inventions in FSHD therapeutics. We also manage challenges with nanoparticle-based methods for clinicalpractice, involvingdeficits in pro-longed safety, flexibility, and capability. By incorporatingperceptions from the molecular level genetics of FSHD and developments in nanomedicine in other muscular dystrophies, this review seeks to ensure aextensive

interpretation on the prospects of nanotherapeutics and to overview future strategies for their clinical application in FSHD.

KEYWORDS: Facioscapulohumeral Muscular Dystrophy (FSHD), DUX4 Gene, Nanotechnology, Nanoparticles, Targeted Drug Delivery, Gene Therapy, Nanotherapeutics, Skeletal Muscle, Muscle Dystrophy, Therapeutic Approaches**.**

1. INTRODUCTION

FSHD (Facioscapulohumeral muscular dystrophy) is one of most predominant neuromuscular disorders that trouble males and females of all ages. It ranks as the third most common autosomal muscular dystrophy across the world.[1] The disease was identified in 19th century by French Neurologists Landouzy & Dejerine. The disease is distinguished by progressive, asymmetrical muscle atrophy, that mainly affects the facial region, upper limbs, lower limbs. It is caused by the abnormal activation of the transcription factor DUX4(Double homebox4) in the skeletal muscle. DUX4 is a morphogenetic transcription factor, that plays a vital role in embryo's early stages. The association of the FSHD & DUX4 explains the mechanisms that are associates with pathology of diseases and consequences of its over expression.[2]

The major genetic subdivisions are FSHD1 & FSHD2, mostly 95% of the cases are sub categorised containing less than 10 units. It takes place because of concentration of the D4Z4 microsatellite reoccur arrangement on chromosome 4q35 to 1-10 perform again in patients. In comparison with healthy human subjects are commonly associated with 11 to over 100 repeats of these units1. Reducing of these repeats consequently results in partial relaxation and hypomethylation, as a result causing ectopic expression of double homeobox 4. This contraction effects the normal function of chromatin structural arrangement and suppresses H3K9me3 methylation, by this means contributing to unconventional activation of DUX4 in skeletal muscle tissue. In comparison with FSHD2 is resulting from haploinsufficiency or impairment of function mutations in gene mediates D4Z4 methylation, ultimately resulting in generalized hypomethylation throughout the D4Z4 set as an alternative to restriction to the distal repeat. The DUX4 gene is a retrogene, exists in the D4Z4 area(~ 3.3 kb) with restricted expression to germline cells and initial embryonic phases, however it retains its inactive state in somatic tissues.[4] Although abnormal activation of DUX4 in somatic cells results in FSHD disease pathological process as it involves cellular destruction, oxidative stress, and inflammation, and influence myogenesis.

To establish stabilization and gene expression form its transcript, DUX4 needs a functional polyadenylation signal (PAS). This functional process PAS is found in the 4qA allele, placed downstream of the highly abundant D4Z4 array inside a characteristic 260-base pair arrangement designated as PLAM, subsequently followed by a 6.2 kb beta-satellite tandemly repeat. In comparison, the 4Qb alternative form of gene is deficient in this PAS and is consequently non-supportive for DUX4 expression, emphasizing the significance of allele-particular sequence variationin disease development.[5] Although FSHD2 accounts for about 5% of cases is not associated with greater production of DUX4 expression or a more significant clinical phenotype in comparison with FSHD1. When associated with D4Z4 contraction, these mutations have the potential to a greater extent worsen disease intensity.

From the Figure 1, it compares with FSHD1, patients with FSHD2 sustain a normal-length D4Z4 repeat array, generally comprising of at a minimum 11 units on chromosomes 4q and 10q. In contrast, as a result heterozygous functional deficiency mutations in genes that control chromatin structure and DNA methylation, they express widely distributed hypomethylation in these regions. The primarily important of these are a limited epigenetic modifiers, comprising structural regulation of chromosomes modifiable hinge domain consisting 1 (SMCHD1), which acts though chromatic compression and repression at the D4Z4 region; DNA methyltransferase 3 beta (DNMT3B), which catalyses novel DNA methylation; and ligand-dependent nuclear receptor-interacting factor 1, a chromatin-connected factor that associates with SMCHD1 to strengthen transcriptional inactivation.In the past decides experimental methods such as Southern blotting, pulsed-field gel electrophoresis, and linear gel electrophoresis have been utilized for the molecular diagnosis.[6]

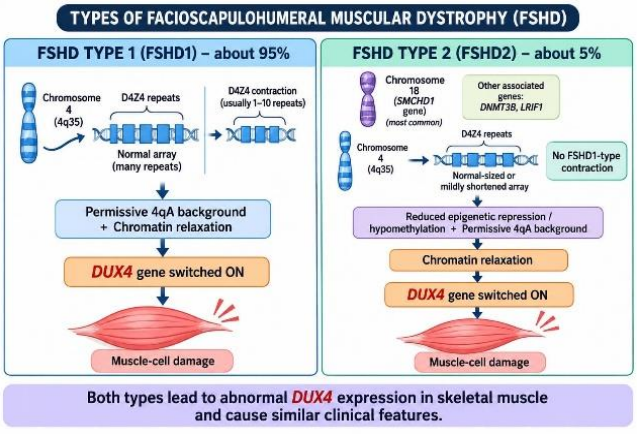


Figure 1: Types of facioscapulohumeral muscular dystrophy.

Recent research findings suggest that the overall risk of cancer in patients with FSHD does not appear to be considerably increased compared with that of overall population. However, several latest research indicates potential elevation occurrence of gastrointestinal malignancies within patients over aged more than 40. Characterization of DUX4 modification, especially in DUX4-rearranged B-cell acute lymphoblastic leukaemia (DUX4-r-B-ALL), continues to be technically challenging.[7] Figure 2 explains about the cytogenetic techniques for example G-banded karyotyping, fluorescence in situ hybridization(FISH), and SNP set analysis frequently unable to determine these rearrangements due to the fact that they are conventionally small, found in proximity to telomeric territories, and entail highly repetitive D4Z4 sequences which may be lead to cross-hybridization and misleading adverse results.[8]

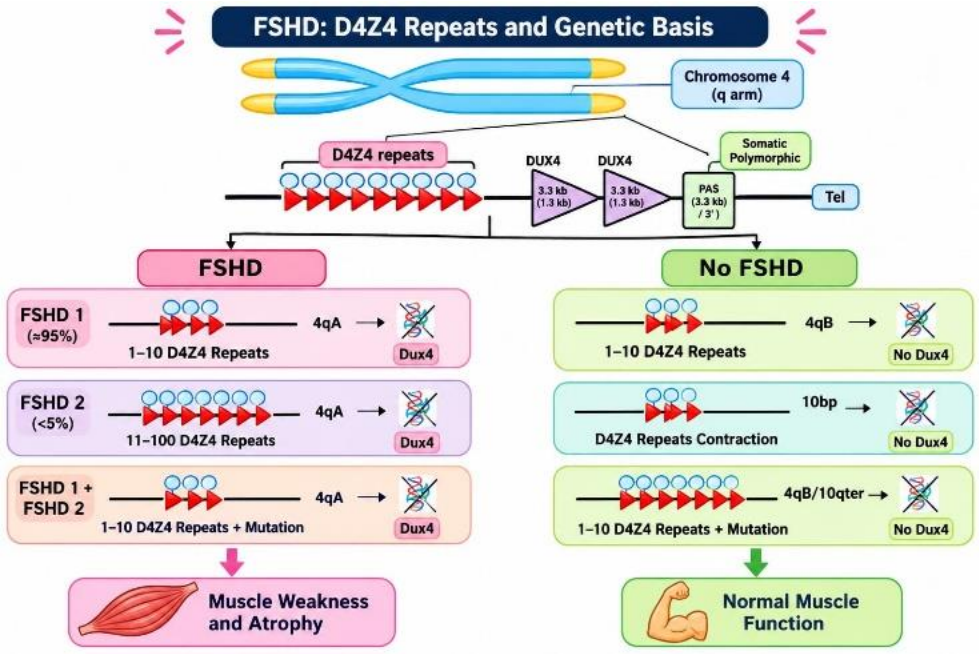


Figure 2: Genetic basis in molcular mechanism of FSHD.

FSHD therapies are now specifically investigated on targeting DUX4, the underlying disease mechanisms. Preclinical improves (antisense oligonucleotides, siRNA/miRNA, gene editing) have demonstrated substantial DUX4 decrease and enhanced cell health of muscles. Some drugs have attained patients: the p38 inhibitor losmapimod reduced fat accumulation on MRI and indicated points of functional benefit, however did not achieve its primary molecular endpoint.[8] Drugs that exclusively enlarged muscle (like myostatin inhibitors) additionally failed to enhance strength. Adapted drugs (albuterol, diltiazem, vitamins) produced limited or

inconclusive outcomes. The main implication is that suppressing DUX4 or its toxicity may change disease, although older anabolic or antioxidant strategies have weak evidence.[9]

2. Therapeutic Limits in FSHD

In spite of considerable research into the molecular biology of FSHD, it continues to be primarily focused on management of symptoms and additional treatments. Treatment methods for example specific physiotherapy activitiesfocused on preserving muscle function, orthopaedicstherapies like scapular fixation to enhance shoulder movement, and supportive devices along with walkers and wheelchairs for the stability of patient loss, have been utilized. Meanwhile these therapeutic approaches evidentlyenhance physical and physiological well-being, they are incapable of changing the course of the disease.[10] During the last few decades, pharmacotherapeutic approaches have mainlyunable to produce uniform or substantial improvement. Albuterol-β2- adrenergic agonists initially identified some possibility in increasing muscle mass and specific muscle-strengthening activities. On the other hand, future investigationsidentified restricted advantages in total function and focused on important adverse effects, involving rhythmic movements and sleep alterations. Similarly, corticosteroids such as prednisone, commonly used in different muscular dystrophies, demonstrated minimal enhancement in muscle strength in FSHD.

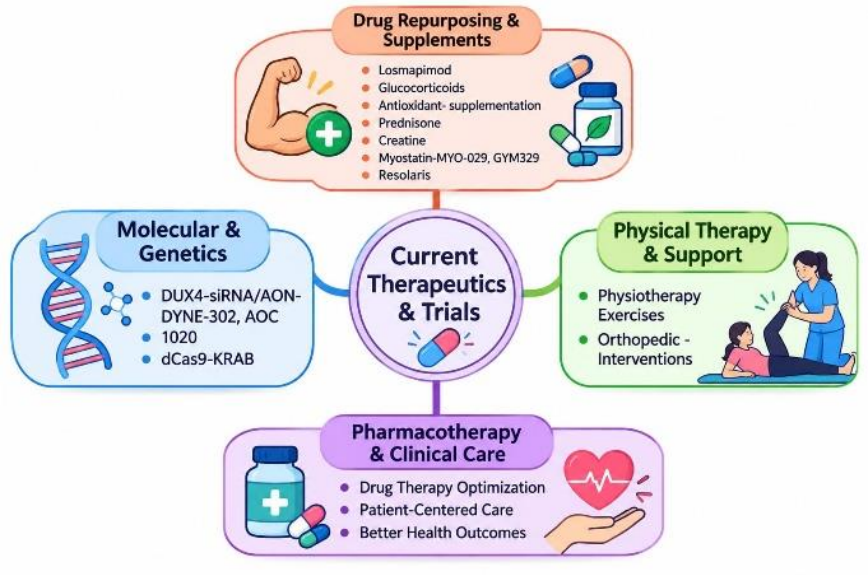


Figure3: Current Therapeutic approaches and clinical trails in FSHD.

All studiesindicated that effective FSHD clinical trials could include out-come assessment methods as the disease initial phase and gravitymodifies frequently. Hence, outcome assessments in studies and clinical studies are commonlydivided into three main groups:

Human studies, which focuses on observation of the patient's physical performance and disease development.[11] There are patient-described results, that solicit patients' own data through surveys, for example FSHD Health Index and the FSHD Rasch-built broadly physical disability measure, to collect their individual experience of the disease. The third and mainvital point is thebiomarkers measurement, suggesting disease identification, analysing therapeutic response, or examine safety. Incorporation of enhanced clinical evaluation, specifically the FSHD integrated operational index and technology-based biomarkers originated from electronic wearables, is increasing the awareness of clinical studies and allowing customised evaluation of disease development and therapeutic response.[12]

3. Nanoparticle platforms in Muscular Dystrophy therapeutics

3.1 Introduction to Nanoparticles

Nanoparticles (NPs) are particles of varying sizes extending from 1 to 200 nanometers. Resulting from their Adjustableto physical and chemical parameters and directed drug-delivery capabilities, NPs have considerably brought major changes to disease treatment across a throughout the several Healthcare fields. Currently, above 60 nanomedicine preparations have been permitted for medical application, including therapeutic uses in oncology (*e.g.*, Doxil and Abraxane), iron replacement therapies (*e.g.*, Ferumoxytol), antifungal medications (*e.g.*, Ambisome), retinal degeneration, anaesthetic agents, and alsorarely observed in inheriteddisorders.[13]

Due to their structure, particle dimensions and surface charge distribution, nanoscale particles can efficiently move insidecells through various pathways. After incorporated, they enhance thecontrolled insidecellular delivery of therapeutic agents,There-foreallowingchange of signal transmissionmethods and gene representation torepair disease.Recent, research has focused on both passive and active focusingmechanisms using nanoscale particles, demonstratingdevelopment in clinical indices, along with environment-responsive nanoparticles that can reply to exactcauses such as pH changes, enzyme function, reactive oxygen species (ROS), or thermal condition.[14] According to their structural organisation, nanoparticles are widely classified into inorganic and organic systems, each with special benefits in healthcare uses. The completeclassification and characteristics have been of these nanoparticles completely examined in the publications.

3.2 Nanoparticle-mediated drug delivery and drug repurposing

Drug reutilizingspeeds upmedical application and lower expensive by using previously available information of about a drug's safety, how it works in the body and its mode of action. It alsoincreases possibility to identify effective therapies for complex diseases like MDs more rapidly.[15] Nano based carrier technique and drug reutilizing can be integrated to improvemedical effectiveness, specificdelivery, and regulateddischarge and decreasebody-wide adverse effects. For example, rapamycin, an immunosuppressing drug and mTOR (mammalian target of rapamycin) blocking agents, is recognised to improve cellular self-cleaning and as a resultreduce muscle injury. Nevertheless, rapamycin by itself, even at 4 times the medically suggesteddose taken by mouth, did not considerably enhancebody muscle power in mdx mice. These drawbacks are mainlylinked to inadequate body tissue delivery and dose-relatedharmful effects, which reduces its medical applications in MDs. Perfluorocarbon (PFC)-derived nano sized particle transport systems have been evaluated to overcome these challenges. PFC-NP, because of their chemistry related and living system lack of reactivity, lowered the probability of unwanted effects from extended administration. Administered through a vein rapamycin NPs substantiallyraised grippingpower and enhancedheart related contracting ability, showingbetterdrug availability in the body and muscle delivery after only eight therapy sessions.[16] Figure 4 illustrates about the functionalization of various nanocarriers targeted FSHD theraphy.

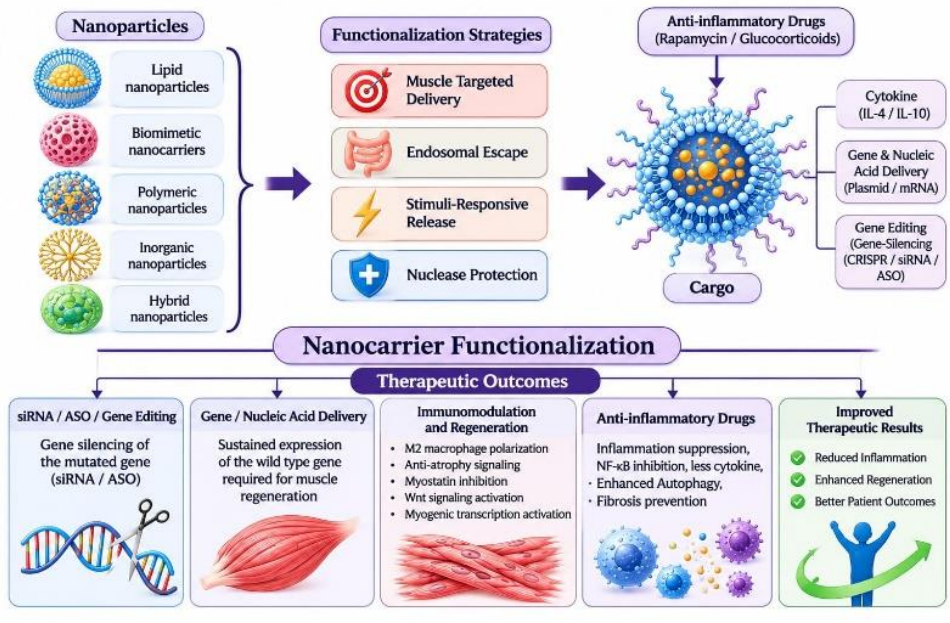


Fig 4 : Funtionailised Nanocarriers for targeted FSHD theraphy.

Further example is Pentamidine (PTM), an FDA-authorised antiparasitic drug, which has been repositioned to manage splicing abnormalities in myotonic dystrophy type 1 (DM1) Although its harmful effectsrestrict its medical use.[17] Even, PTM enclosed in compatible with living tissues and natural decomposable substances, including hyaluronic acid (HA) and poly(l-arginine) obtained nanosized particles, displayedvery lowharmful effects in experimental situationconducted on C2C12 cells. HA, a importantpart of the outside the cell structure, performs major function in muscle recovery and renewal by connecting with CD44 receiving proteinscommonly found on outer cell layer. This researchdemonstrated escape from endosomes employing hyaluronic acid-derived nanocarriers. More-over, *ex vivo* experiments verified successful absorption of nanoparticles by skeletal muscle cells, and an extra reducing in nuclear spots in a new DM1 cellular model.

3.3 Nanoparticles for immunomodulation and regeneration

In patients with muscular dystrophy, immune-mediated inflammation is frequently observed, which leads from the migration of immune cells, including T-cells. Such inflammatory reactionshave an important role in the progression of muscle tissue formation. Hence, a more effective therapy may involve in a combined treatmentalong with cytokines with anti-inflammatory activity and muscle-regenerative factors. In addition, therapeutic delivery, nanoparticles are widely utilized in immune regulation and muscle repair.

In an innovative investigation named PA4 therapy, gold NPs (AuNPs) were linked to IL-4 (and possibly IL-10), attaining a fourfold increase in muscle contractile force and speedwithin two weeks in mdx mice. Cytokines including IL-4 and IL-10 are widely recognised for enhancing immune reactions and muscle restoration by activating M2 macrophages and promoting muscle regeneration.[18] However, these signalling moleculesneedtargeted administration to produce beneficial effectswithout causing adverse effects. Injectable preparations, such assilver nanoparticles (AuNPs), capable of to administer therapies selectively to muscle tissues while reducing toxic effects and immunological reactions in human subjects, provide a potential strategy. This approachutilizes immunomodulation to enhance muscular performance, showingthe ability of nano particles to specifically transport cellular signalling proteins.[19]

Among different Nano particles, dendrimers have developed as potential nanoscale structures in pharmaceutical uses. Such extensively branched, surface-functionalizablepolymeric materials are nanometre-sized, readily soluble in water, and biologically compatible, and

possess clearly defined molecular masses.[20] These structures inner cavities and multivalent surfaces and render them for suitable vehicles for nontoxic and effectivetherapeutic transport.

3.4 Nanoparticles for gene and nucleic acid delivery

In addition to polypeptide and cytokine delivery, the advancement in nanoparticle-derived gene and nucleic acid transfer is also a significantprogress in managing MDs. They provide a practicalsubstitute to conventional AAV viral vector-based therapy, which present threats of intense acquired immunological reactions, along with limited encapsulating and tissue selectivity.[21] hence, investigators are progressivelyinvestigating the possibility of NPs for gene delivery. In Recentstudies, R-HAp NPs (∼calcium phosphate core, surface-modified with arginine) have been utilised to transfercompletedystrophin plasmids (∼18.8 kb) to initial mouse and human myocytes and patient originated cells. Particularly, successfulproduction was attained with just 50 ng of plasmid, 20× less than Lipofectamine 3000, with prolonged mRNA/protein expression for as long as a week.[22] This virus free, Economical approach addresses AAV size restrictions and viral immunogenicity; nevertheless, *in vivo* studies are remained to be conducted to show its effectiveness in an experimental animal system.

Likewise, highly branched poly (ester amine) (PEA)-based NPs displayedhigh within the cell transport and stability in serum during the transfer of plasmid genetic material to mdx mice and muscle cell varieties (C2C12 myoblasts, human skeletal cells). They withstand serum-mediated disintegration and DNase breakdown, allowingreduced quantities and prolonged expression with very low cellular toxicity.[23] Moreover, in an immunologically weakened mdx model, lipid-coated mesoporous silica nanoparticles showedincreasing biological compatibility, reducednon-specific accumulation, and possibility for drug load delivery along with imaging techniques. Although, when evaluated at variouslevels with extendedexposure periods, these nanoparticles demonstrated harmful effects in primary human muscle precursor cells in comparison with polymer-based nanoparticles.

4. Nanotherapeutics in muscular dystrophy: lessons and prospects in FSHD

The use of nanocarriers in FSHD is poorly investigated. Therefore, whereas evaluating nanotherapeutics for muscular dystrophies like FSHD, the formulation of approach to identify repairing muscular tissue biomarkers or FSHD signals for enhancedaccuracy and effectiveness is essential. In a particular investigation, upon modified with muscle-targetingbinding moleculesincluding M12 peptides, A2G80, and ASSLNIA, NPs have showedsignificant selectivity in experimental models, allowing the recovery of dystrophin or

the direct transport of therapeutic material to affected muscle tissues.[24] These Advanced delivery systems decrease the necessarydrug dosage and reducenon-specific effects, necessaryfactor for genetic treatments, which are alternativelyrestricted by immune-stimulating potential and poor systemic dispersion when administered*via* viral-based carriers like AAV. There is aoccurrence of 70% anti-AAV in the study group, and its immunological detection through the stimulation of capsid-specific CD4+ helper and CD8+ cells leads to the immune-related toxicity related to AAV-based gene delivery.[25]

Additionally, the primary importance of the muscle selectivity, nanotherapeutic approaches for FSHD need to address the disease-related local environment, involvingmodifications in the ECM, oxidative damage, inflammatory response, immune cell accumulation, and reducedmuscle formation and muscle repair.[26] Nanoparticle surface modificationapproaches like ECM-breakingbiological catalyst (*e.g.*, bromelain) and TGF-β pathway inhibition providepotentialremedies to eliminatetissue barriers and increase nanoparticle entry, preservation, and treatment effect.

To reduce the impacts of inflammatory response, macrophage differentiation can be one possible strategy. Macrophages are found in large numbers at the location of muscle repair. Whenever there is muscle damage, monocytes develop into inflammation-promoting Ly6C + M1 macrophages.[27] Additionally, this drawsextra monocytes, improves the clearance of cellular fragments, and stimulates the conversion of M1 macrophages into anti-inflammatory response Ly6C − M2 macrophages, which promote the multiplication of muscle precursor cells. A disturbance in the conversion from M1 to M2 macrophages can disturb the muscle healing process.[28] Research indicates that AuNPs, due to their optimal structure, size, and surface alteration, can regulate M2 macrophage polarization to encourage tissue repair and regeneration viamechanisms like p38 MAPK. In the same manner, zinc-dihydromyricetin (Zn-DHM) nanozyme TiO_2 nanotubes and CeO_2 nanoparticles have been found toassist macrophage conversion from the pro-inflammatory M1 state to the repair-promoting M2 state, promoting muscle regeneration and enhancing anti-inflammatory biomarkers.

5. Challenges and limitations in FSHD treatment

As a result of the variability of clinical features and the genomic complexity of disease development, formulatingaestablished and therapeuticapproach to FSHD has shown to be difficult, and similar to other uncommon disorders, FSHD may more frequently lead todelayed or incorrect diagnosis. The variation in clinical severity and development makes it

complicates for clinical investigations to sufficientlyevaluates therapies due to the diversepatient-specific disease progression.[29] At present, there continues no individualsuccessful treatment for FSHD instead of an integrated approach, and while multipledrug trials have demonstratedearly potential, they have not established adequate treatment of the disease. Investigating the utilization of genetic treatment in regulating DUX4 in these individuals has been challenged by the abnormal feature of DUX4 activity in the disease condition and a small number of naturally occurring mammalian models, in absence of which human investigations may create obstacles.moreover, cell culture based and maturation of FSHD myoblasts are commonlychallenging, with reduced levels and considerable variation of DUX4 expression.[30] Genome analysis of FSHD specific regions utilisingadvanced identifications and analytical toolsis affected by elevated expenses, shortage of procedures due to limitations, lack of facilities and specialised knowledge, and insufficient evaluationin extensive investigations. As discussed earlier, antisense oligonucleotide treatment also exhibit possibility in the treatment of FSHD, but experiencing difficulties due to non-specific effects, reduced absorption in muscular tissue, and elevatedprojected cost and when they enter the market. Therefore, future research is required to improve clinical study planning in FSHD and completely clarify the most potentialmolecular mechanisms to focus on disease-altering treatments.

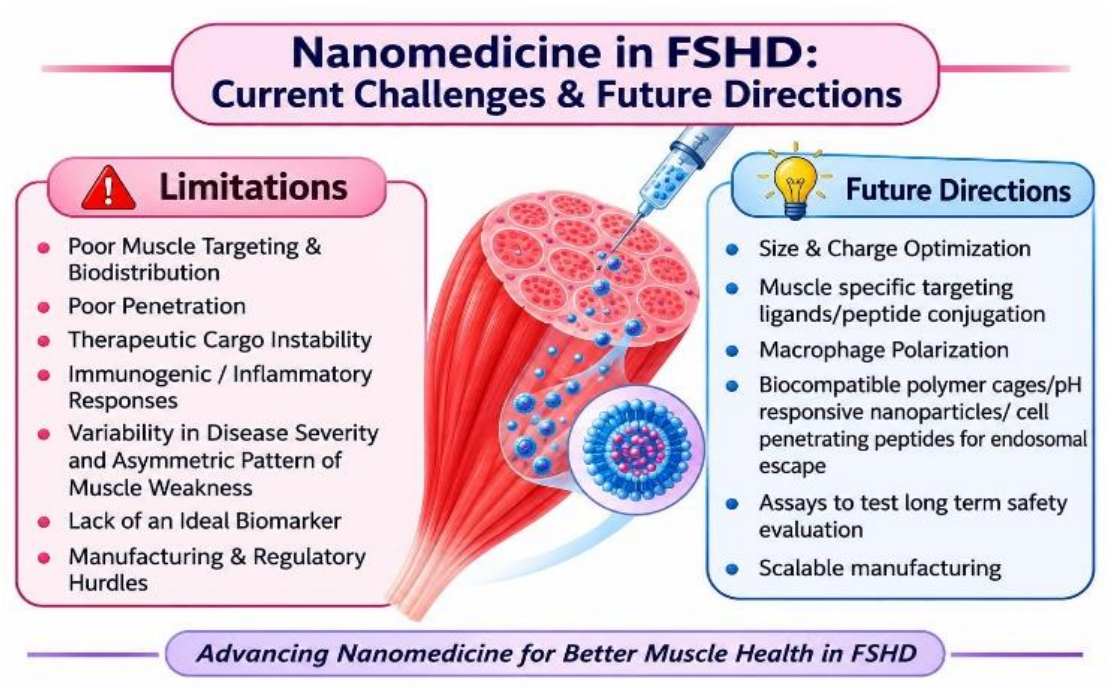


Figure 5: Transforming FSHD treatment: Nanomedicine challenges and emerging opportunities.

6. Future perspectives

FSHD describesimportantissuesbecause of its continuous development, difference in clinical presentation, and the lack of disease-alteringtherapies. This review shows the differentenvironment of FSHD treatment, involving pharmacologic management, physiological therapy, and exercise procedures, along with the use of supportive devices and surgical protocol. Developing therapeutic innovations, such as gene-targeted procedures, antisense oligonucleotides, myostatin blocking agents, and CRISPR-Cas9 technologies, shows promising pathways for managing the genetic and molecular basis of the disease.[31]

Future investigations in the therapies and treatment of FSHD should highlightsdifferentimportant points to handle the present therapeutic deficiency and enhance patient response. Improvements in genomic therapy, mainly in DUX4 suppression and CRISPR-Cas9 technologies, offer substantialpossibilities. Moreover, continuingclinical studies is needed to reduce delivery systems, inhibit off-target effects, and increase safety and effectiveness in clinical studies. Further, given the genetic and phenotypic variation of FSHD, individualized treatment methods are important. Recognising biomarkers that can estimate disease development and treatment effect will be essential in modifyingtreatments to particular patients, allowing for more useful and specific care for patients.

Enhancing the design of clinical studies is another preference, as presentstudiesdifficult with the variation in disorder appearance and development. Establishing stratification procedures that leadsto genetic and clinical variations will improve the ability to check therapeutic effectiveness and fasten the growth of disease-modifying therapies. Although, the activity of patient supporting groups in promoting FSHD study cannot be underestimated. These groups are important in saving funding, improving regulatory processes and strengthening awareness, all of which are crucial for overcoming the regulatory and financial limitations that delayed the improvement of novel treatments.

7. CONCLUSION

To conclude, aninterdisciplinary method that combines computer-based representation, large scaleevaluation, and multi-omics data to systematicallyprovide nanocarriers customised to the FSHD muscle microenvironment can provide unparalleledapproaches. However, there are particular drugs that have been acceptednewly in clinical trials– mRESVIA (mRNA-1345)(NCT07117487, NCT05127434), which shows aencouragingprospects of nanodrugs in the treatment of FSHD by offering new opportunities for more effective and specific

treatments. Additionally, to completely achieve the capability, maintain biological safety, and attain prolonged biological compatibility, comprehensiveinvestigation is essential.

ACKNOWLEDGEMENT

We thankful to the management of Dr Samuel George Institute of Pharmaceutical Sciences for the providing of necessary facilities for the carry out of this review article. Our sincere thanks to the faculty who provided the assistance to complete the work.

8. REFERENCE

1. Deepali Shukla, Indrani Talukdar, Meenal Kowshik; Nanoparticle therapeutics in FSHD: current research and future perspectives. Nanoscale, 2026; 18(26): 13700–13715.
2. Himeda CL, Jones PL. FSHD therapeutic strategies: what will it take to get to clinic?. Journal of Personalized Medicine, 2022 May 25; 12(6): 865.
3. Cohen J, DeSimone A, Lek M, Lek A. Therapeutic approaches in facioscapulohumeral muscular dystrophy. Trends in molecular medicine, 2021 Feb 1; 27(2): 123-37.
4. Reddy, A.K., Preeti, N., Subramaniyan, R., Vardhanan, H., Adalarasan, S. and Balasubramani, K., 2026. Advancements in Diagnostics and Therapeutics in Facioscapulohumeral Muscular Dystrophy-a Systematic Review. Central India Journal of Medical Research, 5(03): 142-157.
5. Reddy AK, Preeti N, Subramaniyan R, Vardhanan H, Adalarasan S, Balasubramani K. Advancements in Diagnostics and Therapeutics in Facioscapulohumeral Muscular Dystrophy-a Systematic Review. Central India Journal of Medical Research, 2026 Sep 2; 5(03): 142-57.
6. Ragozzino E, Bortolani S, Di Pietro L, Orecchini E, Papait A, Nanni S, Torchia E, Monforte M, Ravera B, Giacò L, Mantini G. RNA cargo profiling of muscle extracellular vesicles identifies candidate biomarkers of disease activity and muscle degeneration in FSHD. Journal of Translational Medicine, 2026 Feb 25; 24(1): 332.
7. Bayazit MB, Nagaraj CK, Newell JS, Nguyen KT, Rima XY, Doon-Ralls J, Reátegui E, Statland JM, Tawil R, Flanigan KM, Harper SQ. Plasma EV Proteomics Identifies ECM Remodeling and Inflammatory Proteins LUM and C7 as Candidate Biomarkers in FSHD. Annals of Clinical and Translational Neurology, 2026 May 20.
8. Bishnupriya UB, Mohapatra D. Opportunities and challenges of nanomedicine for muscular dystrophy. Nanomedicine, 2026 Sep 28: 1-4.

9. Colapicchioni V, Millozzi F, Parolini O, Palacios D. Nanomedicine, a valuable tool for skeletal muscle disorders: Challenges, promises, and limitations. Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology, 2022 May; 14(3): e1777.
10. Shukla D, Talukdar I, Kowshik M. Nanoparticle therapeutics in FSHD: current research and future perspectives. Nanoscale, 2026 Jul 9; 18(26): 13700-13715. doi:10.1039/d6nr01374k. PMID: 42301101.
11. Mariot V, Bloch RJ, Badiani R, Bugiardini E, Dumonceaux J. Spatiotemporal DUX4 toxicity in FSHD: from epigenetic derepression to biomarker-driven targeted therapies. Neuromuscul Disord, 2026 Jun; 63: 106420. doi:10.1016/j.nmd.2026.106420. Epub 2026 Mar 31. PMID: 42066431.
12. Duranti E, Villa C. Influence of DUX4 Expression in Facioscapulohumeral Muscular Dystrophy and Possible Treatments. Int J Mol Sci, 2023 May 30; 24(11): 9503. doi:10.3390/ijms24119503. PMID: 37298453; PMCID:PMC10253551.
13. Augustinus R, Voet N, de Greef JC, Voermans NC. Recent progress in the molecular understanding and treatments of facioscapulohumeral muscular dystrophy. Curr Opin Neurol, 2025 Oct 1; 38(5): 504-512. doi:10.1097/WCO.0000000000001382. Epub 2025 Jun 5. PMID: 40471677.
14. Beck SL, Yokota T. Oligonucleotide Therapies for Facioscapulohumeral Muscular Dystrophy: Current Preclinical Landscape. Int J Mol Sci, 2024 Aug 21; 25(16): 9065. doi:10.3390/ijms25169065. PMID: 39201751; PMCID:PMC11354670.
15. Chen JC, King OD, Zhang Y, Clayton NP, Spencer C, Wentworth BM, Emerson CP Jr, Wagner KR. Morpholino-mediated Knockdown of DUX4 Toward Facioscapulohumeral Muscular Dystrophy Therapeutics. Mol Ther, 2016 Aug; 24(8): 1405-11. doi:10.1038/mt.2016.111. Epub 2016 Jun 3. PMID: 27378237; PMCID:PMC5023379.
16. Jones TI, Chew GL, Barraza-Flores P, Schreier S, Ramirez M, Wuebbles RD, Burkin DJ, Bradley RK, Jones PL. Transgenic mice expressing tunable levels of DUX4 develop characteristic facioscapulohumeral muscular dystrophy-like pathophysiology ranging in severity. Skelet Muscle, 2020 Apr 11; 10(1): 8. doi:10.1186/s13395-020-00227-4. PMID: 32278354; PMCID:PMC7149937.
17. Oliva J, Galasinski S, Richey A, Campbell AE, Meyers MJ, Modi N, Zhong JW, Tawil R, Tapscott SJ, Sverdrup FM. Clinically Advanced p38 Inhibitors Suppress DUX4 Expression in Cellular and Animal Models of Facioscapulohumeral Muscular Dystrophy. J Pharmacol Exp Ther, 2019 Aug; 370(2): 219-230. doi:10.1124/jpet.119.259663. Epub 2019 Jun 12. PMID: 31189728; PMCID:PMC6652132.

18. Lim KRQ, Bittel A, Maruyama R, Echigoya Y, Nguyen Q, Huang Y, Dzierlega K, Zhang A, Chen YW, Yokota T. DUX4 Transcript Knockdown with Antisense 2'-O-Methoxyethyl Gapmers for the Treatment of Facioscapulohumeral Muscular Dystrophy. Mol Ther, 2021 Feb 3; 29(2): 848-858. doi:10.1016/j.ymthe.2020.10.010. Epub 2020 Oct 15. PMID: 33068777; PMCID:PMC7854280.
19. Lim KRQ, Nguyen Q, Yokota T. DUX4 Signalling in the Pathogenesis of Facioscapulohumeral Muscular Dystrophy. Int J Mol Sci, 2020 Jan 22; 21(3): 729. doi:10.3390/ijms21030729. PMID: 31979100; PMCID:PMC7037115.
20. Chen JC, King OD, Zhang Y, Clayton NP, Spencer C, Wentworth BM, Emerson CP Jr, Wagner KR. Morpholino-mediated Knockdown of DUX4 Toward Facioscapulohumeral Muscular Dystrophy Therapeutics. Mol Ther, 2016 Aug; 24(8): 1405-11. doi:10.1038/mt.2016.111. Epub 2016 Jun 3. PMID: 27378237; PMCID:PMC5023379.
21. Beck SL, Yokota T. Oligonucleotide Therapies for Facioscapulohumeral Muscular Dystrophy: Current Preclinical Landscape. Int J Mol Sci, 2024 Aug 21; 25(16): 9065. doi:10.3390/ijms25169065. PMID: 39201751; PMCID:PMC11354670.
22. Fox A, Oliva J, Vangipurapu R, Sverdrup FM. SIX transcription factors are necessary for the activation of DUX4 expression in facioscapulohumeral muscular dystrophy. Skelet Muscle, 2024 Dec 3; 14(1): 30. doi:10.1186/s13395-024-00361-3. PMID: 39627769; PMCID:PMC11613756.
23. Lim KRQ, Yokota T. Knocking Down DUX4 in Immortalized Facioscapulohumeral Muscular Dystrophy Patient-Derived Muscle Cells. Methods Mol Biol, 2023; 2587: 197-208. doi:10.1007/978-1-0716-2772-3_12. PMID: 36401032.
24. Knox RN. Facioscapulohumeral Muscular Dystrophy. Continuum (Minneap Minn), 2025 Oct; 31(5): 1329-1343. doi:10.1212/cont.0000000000001614. Epub 2025 Oct 2. PMID: 41037169.
25. Himeda CL, Jones PL. The Genetics and Epigenetics of Facioscapulohumeral Muscular Dystrophy. Annu Rev Genomics Hum Genet, 2019 Aug 31; 20: 265-291. doi:10.1146/annurev-genom-083118-014933. Epub 2019 Apr 24. PMID: 31018108.
26. Hamel J, Tawil R. Facioscapulohumeral Muscular Dystrophy: Update on Pathogenesis and Future Treatments. Neurotherapeutics, 2018 Oct; 15(4): 863-871. doi:10.1007/s13311-018-00675-3. PMID: 30361930; PMCID:PMC6277282.
27. Belayew A, Rosa AL, Zammit PS. DUX4 at 25: how it emerged from "junk DNA" to become the cause of facioscapulohumeral muscular dystrophy. Skelet Muscle, 2025 Aug

25; 15(1): 24. doi:10.1186/s13395-025-00388-0. PMID: 40855454; PMCID:PMC12376486.

28. Ghasemi M, Emerson CP Jr, Hayward LJ. Outcome Measures in Facioscapulohumeral Muscular Dystrophy Clinical Trials. Cells, 2022 Feb 16; 11(4): 687. doi:10.3390/cells11040687. PMID: 35203336; PMCID:PMC8870318.
29. Nakamura K, Ortuste Quiroga HP, Horii N, Fujimaki S, Moroishi T, Nakayama KI, Hino S, Saito Y, Nishino I, Ono Y. Iron supplementation alleviates pathologies in a mouse model of facioscapulohumeral muscular dystrophy. J Clin Invest, 2025 Jul 1; 135(17): e181881. doi:10.1172/JCI181881. PMID: 40591405; PMCID:PMC12404756.
30. Jones TI, Chen JC, Rahimov F, Homma S, Arashiro P, Beermann ML, King OD, Miller JB, Kunkel LM, Emerson CP Jr, Wagner KR, Jones PL. Facioscapulohumeral muscular dystrophy family studies of DUX4 expression: evidence for disease modifiers and a quantitative model of pathogenesis. Hum Mol Genet, 2012 Oct 15; 21(20): 4419-30. doi:10.1093/hmg/dds284. Epub 2012 Jul 13. PMID: 22798623; PMCID:PMC3459465.
31. Lu-Nguyen N, Malerba A, Antoni Pineda M, Dickson G, Popplewell L. Improving Molecular and Histopathology in Diaphragm Muscle of the Double Transgenic ACTA1-MCM/FLExDUX4 Mouse Model of FSHD with Systemic Antisense Therapy. Hum Gene Ther, 2022 Sep; 33(17-18): 923-935. doi:10.1089/hum.2021.251. Epub 2022 Apr 28. PMID: 35078334.