A New Genetic Insight for Orphan Renal Disorder, Fabry: A Review

Pragati Karemore a, Dinesh Kumar a and Anil Kumar a*

a Department of Biotechnology, Govt. V. Y. T. PG. Autonomous College Durg, Chhattisgarh, India.

Authors’ contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

ABSTRACT

Fabry is the rare X-linked genetic disorder caused due to mutation in Alpha –Galactosidase encoding GLA gene mutation in chromosome number 22. It has wide diversification in prevalence due to clinical heterozygosity. There are some potential biomarkers for the evaluation of normal or altered genes responsible for Fabry. Advances in the research of biomarkers over the years have made significant development for several clinical indicators, viz. urine-derived cells, oxidative stress, DNA methylation, etc. At present days the recommended therapies for the disease are Enzyme Replacement Therapy (ERT), Chaperone therapy (CT), and mRNA-based therapy, besides, some second-generation therapies which are still under clinical trials.

Keywords: Rare inherited disease; genomic variants fabry; biomarker; diagnostics; treatment.

1. INTRODUCTION

Fabry disease is a rare renal disorder caused by mutation of the X-linked GLA gene which results in the deficiency of alpha-galactosidase [1]. The cells which are deficient in the alpha-galactosidase enzyme can not metabolize glycosphingolipid mainly Globotriaosylceramide (GB3) [2-7]. Accumulation of GB3 can lead to various symptoms and for the progression of the cascade (series of progressive events) rather than deficiency of enzymes so maybe a diagnostic tool for the detection of Fabry disease [8]. GB3 cannot gain its original metabolized form Alpha-D-Galactosyl residue which is the end product of the reaction and gets clustered in
higher accumulation of Globotriaosylceramide in lysosomes of cells and tissues. It belongs to renal lipidosis and may accumulate into different organs which causes multisystem disease [9].

Fabry prevalence is associated with a wide range in white male population approximately 1:17000 to 1:117000, in which early manifestation mutation is seen in 1:22000 to 1:40,000 in males; advance onset manifestation has been reported in about 1:6000 to 1:40,000 in females and 1:1000 to 1:3000 in males [9]. European database which reports about check on the efficiency, potential, and safety of Enzyme Replacement Therapy with algalsidase alpha and considering to monitor cardiac events in Anderson Fabry Disease is an outcome of “Fabry Outcome Survey” [10].

In India, the estimated data for the prevalence of Fabry disease is 1/40000 to 1/117000 is of live birth and includes both classical and non-classical phenotypes [11].

There are two major forms of Fabry based on enzymatic activity-

1.1 Classical Form
- Lesser amount enzymatic activity [12].
- Early manifestation [11].

1.2 Attenuated Disease/Nonclassical
- A high amount of enzymatic activity [13].
- Later manifestation [12].

The rarity of Fabry made it difficult to understand the mechanism. Age and onset are variable, a person with unknown family history is diagnosed in later life, the reason for later onset detection is the slower progression of detectable alpha-galactosidase and causes less damage to the organs. Glomerular mesangial illness, vacuolated epithelial cells, lipid inclusions are the signs of renal abnormality. The early detection of proteinuria is the apparent sign of abnormal renal dysfunction that leads to renal failure in many individuals before the treatment methodology was developed like Enzyme replacement therapy [12].

Fig. 1. Conundrums of evidence
Table 1. Characterization of classical and non-classical fabry

| Classical | Non-classical |
|-----------|---------------|
| Early symptoms such as anhydrosis and neuropathic pain result in severe phenotype in Hemizygous males. Mostly null mutants, No residual enzyme activity at early onset. Event rate high | Asymptomatic to the involvement of some indispensable organs in the female heterozygote. A high amount of enzyme activity on later onset. Event rate low |
| Women-1.54 to 5.40 | Men-3.17 to 10.00 |
| Women develop more complications; major organ complications diagnosed early at the age of 20 to 30 years | Non-classical Fabry develops Less complication at their 50s. |
| Men show lower GFR, higher left ventricular mass, and elevated plasma | Comparatively high GFR, low ventricular mass, and plasma with less globotriaosylsphingosine |

2. GENETIC ARCHITECTURE OF FABRY

There may be huge clinical variations among the same family mutation which creates difficulty in its diagnosis and men can be diagnosed only if the residual enzyme activity is found to be <35% of the mean. Females’ heterozygote shows high enzyme activity due to mosaic (random inactivation) in later stage and which shows the involvement of few organs only [14]. Gla variant with unclear significance is also present and termed as a fringe allele [15].

The deficiency of alpha-galactosidase (GLA) lysosomal hydrolase enzyme (EC 3.2.1.22) causes the accumulation of GB₃ (alpha-linked Galactosyl moiety).³ Prenatal diagnosis and heterozygous carrier identification, candidate identification for enzyme replacement therapy can be made easier with the help of mutation heterogeneity provides molecular pedigree analysis and stability properties [16]. The period involved from the visibility of the first symptom to its proper diagnosis is approximately 15 years, sometimes it may vary from individual to individual and severity of the disease [13]. Alpha-galactosidase enzyme has approx. 1318 nucleotide in the X-Chromosome q22.1 which encodes 429 amino acid long protein chain. In this sequence, 1-31 act as signal peptides, and 32-429 form the main protein. An amino acid from 203 to 207 makes substrate binding region, amino acid 139, 192 & 215 are glycosylation region and amino acid from 170 to 231 makes active region. This region is very important for the normal function of protein and mutation in the region as shown in Table 3, and Fig. 2, showing loss of function in protein (UniProt P06280).

GLA gene mutation is somewhat limited to the uniqueness of the family, there are currently more than 900 Gene variations that have been identified which results in its limitation to the genotype-phenotype positive correlation within the families [17,18].

2.1 Aetiology of GLA Gene and Genomic Variants

A large variety of polymorphisms (Fig. 2 and Table 3) have been reported in GLA variants. Some intronic mutations have been reported as a pathogenic variant of the GLA gene and the mode of mutation comprises nonsense, splice mutation, rearrangements, deletion, and duplication in a wider range [19].

The molecular analysis of classical and nonclassical variants revealed that CpG (5’C-Phosphate-G-3’=Cytosine and Guanine are separated by only one phosphate group) dinucleotide alteration in codon 227 is the epicenter (Mutational hotspot) for most of the mutations in unrelated Fabry alleles, except N215S, R227Q, and R227X mutation [10], viz.-

**Classical Mutation:** N34S, C56G, W340X, W162R, R22Q, R227X, D264V, D266V, S297F, D313Y, G328A, E398X, IVS2+2, IVS5, delta2,3,773 delta 2, delta 5,1123 delta 53,1016 delta 11 [10].

**Asymptomatic:** 1208 delta 3, is the frameshift mutation due to deletion of arginine 404 in a polypeptide of the residual enzyme [10].

**Nonclassical:** N215S shows cardiac and renal manifestation [10].
Karem et al.; JPRI, 33(58A): 563-576, 2021; Article no. JPRI.78861

2.2 Novel Genomic Variants of Fabry Disease

The c.448delG is the de novo mutation, found as a result of a deletion in exon 3 of the GLA gene. Some of the symptoms include vertigo, acroparesthesia, cornea verticilata, and abdominal main [20].

1. In the population of Argentina, two nonclassical missense mutations were found-

p.(Cys174Gly): This mutation causes unfolding by disturbing thermal stability and as a result protein aggregates lead to organ damage [21].

p.(Arg363His): In this case heat shock protein (Hsp 70) in normal condition binds to Arginine (positively charged amino acid) but in mutant form Histidine 363 is unable to bind properly with Hsp 70 causes instability in protein and the transportation to lysosome does not take place [21].

Alpha GAL A: Intron splicing mutation c.801 C > A. It is an insertion mutation that causes shifting of the frame by addition of 36 nucleotide termination sequence TGA in the Exon 5 placing 12 nucleotides downstream causes formation of 270 amino acid residue of truncated GLA protein that declines the mRNA stability with the nonsense-mediated decay approach [22].

2. Genomic variants in India: The genotypic analysis of 54 patients from 37 families were done in India and the data was taken from 10 territory referral centers which revealed 33 GLA gene varieties in 49 FD patients scattered among 7 exons in which 11 novel and 22 unknown variants were found with symptoms related to cardiovascular, ocular and cardiac dysfunction [23] (Table 2).

3. CLINICAL FEATURE

Fabry manifestation has been reported both in males and females; males with severe renal dysfunction and female with heterozygote in early-stage shows renal insufficiency and random inactivation in advance stage besides, non-classical symptoms involving target organs [14].

3.1 Threshold

The appropriate threshold for the detection of Fabry considers 30-35% alpha-galactosidase enzyme activity as the cut-off for diagnosis and for frequent measurement of enzyme activity dry blood spots or peripheral leucocytes are suitable samples [14,24].

The major value for pathogenicity in the form of threshold is still unknown as it varies depending upon the individual to individual and also upon the organ involved [24].

3.2 Associated Risk

Individuals' risk for complications depends not only on the alpha-galactosidase but also on other factors like epigenetic, environmental, and genetic factors which are considered to be the risk factors for the prevalence of Fabry disease [14].

The MRI (Magnetic Resonance Image) of the brain shows the presence of an ischemic cerebral lesion, due to several mutations detected by genetic polymorphism (Table 4) [25,26].

Factor V Leiden mutation and alpha-galactosidase a activity which was seen subsequently in the mouse model confirmed the enhanced thromboembolism along with up-regulation of vascular thrombi level which was not seen in the mouse model alone [14].

3.3 Symptoms

Renal disease is considered to be a potent convict for mortality and morbidity among individuals with Fabry disease [27].

Table. 2 Mutations in exon 5 [23]

| S.No. | Mutation type          | Mutation                      |
|-------|------------------------|-------------------------------|
| 1.    | Missense mutation      | GLA:c657C>G:pIle219Met        |
| 2.    | Nonsense mutation      | GLA:c658C>T:pArg220Term       |
| 3.    | Duplication mutation   | GLA:c683dupA                  |
| 4.    | Small deletion         | GLA:c782delG:p.Gly261Valfs*8  |
As per the diagnosis cascade and screening of relatives for phenocopy identification in patients with inherited cardiomyopathies regardless of the age of the patient, it becomes evident that chromosome inactivation mostly did not manifest any effect in the female carrier but due to random inactivation some discrete symptoms have been observed in affected females [28]. Renal disease is considered to be a potent cause for mortality and morbidity among individuals suffering from Fabry disease [27]. There is enormous variability within clinical courses and symptoms (Fig. 3) of affected people suffering from Fabry disease and the basis of morbidity could be determined with the help of positive family history, severity which leads to morbidity condition showing involvement of renal, cerebrovascular and cardiac ailments.

The affected male shows symptoms like proteinuria, microhematuria, and lipiduria, angiokeratomas, edema, abdominal pain, and acroparesthesia is more often seen in childhood. The main factor for elevated risk is premature stroke, transient ischemic attack, and dementia [29]. Pathogenicity like myocardial, neurophysiological, cerebrovascular, classical-like many symptoms have been observed in the FD patients are useful for diagnosis.
Table 3. Showing mutation causing loss of function of protein

| Residue No. | Mutation (from-to) | dbSNP       |
|-------------|-------------------|-------------|
| 20          | A→D/P             | rs89312134, rs104894847 |
| 36          | L→W              | rs869312138 |
| 40          | P→S              | rs104894831 |
| 42          | M→T              | rs398123201 |
| 45          | L→P              |             |
| 48          | E→D              | rs869312254 |
| 56          | C→Y              | rs869312258 |
| 86          | Y→C              | rs869312140 |
| 91          | I→T              | rs869312141 |
| 91          | I→N              | rs869312141 |
| 94          | C→S              |             |
| 164         | C→Y              | rs113173389 |
| 187         | M→I              | rs869312146 |
| 202         | C→Y              | rs869312344 |
| 204         | w→R              | rs869312148 |
| 227         | R→P              | rs164894840 |
| 247         | S→P              | rs869312393 |
| 262         | W→R              | rs869312154 |
| 269         | V→G              | rs28935488  |
| 276         | S→G              | rs869312432 |
| 317         | I→S              |             |
| 327         | Q→L/R            | rs869312160 |
| 328         | G→V              | rs104894832 |
| 342         | E→K              |             |
| 358         | G→S              |             |

Table 4. Genetic polymorphism in MRI of Fabry patient

| Factors                              | Genetic polymorphism                      |
|--------------------------------------|-------------------------------------------|
| Interleukin-6                        | G174C                                    |
| Endothelial nitric oxide synthase    | G894T                                    |
| Factor V leiden                      | Factor V G161A                           |
| Protein Z                            | A13G                                     |
|                                      | G79A                                     |

4. LITERATURE SEARCH METHOD

Present Review Article has been prepared after a critical review of various kinds of literature articles outsourced from various databases such as PubMed, Shodhganga, Google Scholar, Research Gate, Science direct, WHO(World Health Organization) records with the help of different keywords like Fabry disease, Genomic variants, Correlation with other diseases Biomarker, treatment methodologies, etc.

5. TOOLS FOR DIAGNOSIS AND RESEARCH PATHOMECHANISM

There are many diagnostic tools which are being used as potent diagnostics tools for determination of Fabry disease such as:

- Globotriazlyceramide (GB3) accumulation.
- Primary Urine derived cell cultures
- Oxidative stress biomarkers

5.1 GB3 Accumulation

To check or monitor the efficacy of therapy and the progression of the disease is being monitored with the help of measurement of GB3 accumulation [30].

GB3 accumulation is the potent biomarker because of its direct use as it releases secondary mediators for glomerular Fabry nephropathy and causes disease pathogenesis and progression through fibrosis and inflammation stimulation [30]. In vitro analysis of prime urine-derived cells
showed elevation in the expression level of COL4, FN1, HES1, and TGFβ1 [31].

5.2 Primary Urine-Derived Cells

Urine cells are non-invasive cells of a patient with Fabry disease decreases Alphagalactosidase enzyme activity and that mimics the cellular in vivo model and dysregulation of lysosomal protein, so the finding is based on proteomics, qRT-PCR, western blot, immunoassay, and this may be the prospects for the diagnostic purpose as both show Globotriaosylceramide accumulation (lysosomal storage material) [32].

5.3 Oxidative Stress Biomarkers

Several mutations are found related to oxidative stress revealed the involvement of smooth muscle cells, cardiac myocytes, and all types of renal cells such as podocytes, tubular and glomerular cells. Oxidative stress is responsible for organ damage is a hypothesis considered by several authors [33]. Occurrence of pro-oxidant state induced (Table-5) by Lysosomal Gb3 in Fabry patient had been demonstrated by Biancini [34]. A positive correlation was found as the level of advanced oxidation product increases the reduction of thiol group and ferric reducing power [33], results in a reduction of proteins responsible for oxidative damage [34]. The involvement of mitochondrial DNA haplogroups for modulation of oxidative stress in patients suffering from Fabry was established before the Enzyme replacement event [35]. Elevated Lipid peroxidation showed irreversible effect after Enzyme replacement therapy as per hypothesis [36].

Cardiovascular renal remodeling pathophysiology suggested oxidation stress signaling cascade and activation of oxidative stress and p22phox expression were reported substantially elevated by Ravarotto, et al. [37] Table 6 shows the diagnostic approaches and Table 7 shows the emerging potential tools in the study for diagnosis purposes.

**Fig. 3. Clinical manifestation**
Table 5. Oxidative stress activation [34]

| S.No. | Increase level | Decrease level |
|-------|----------------|----------------|
| 1.    | Erythrocytic Superoxide dismutase/catalase ratio | Anti oxidant scavengers |
| 2.    | Malondialdehyde | Reduced glutathione |
| 3.    | Protein carbonyl group product | Glutathione peroxidase |

Table 6. Current diagnostic approach

| S.no | Diagnostic approach | Characteristics |
|------|---------------------|-----------------|
| 1.   | Serum creatinine and GFR (Glomerulus Filtration Rate) | Increase in GFR-Early detection tool [38], A decline in GFR-Later stage [39], Two different strategies based on serum creatinine equation: Adult-Chronic Kidney Disease Epidemiology Collaboration(CKD-EPI) [40], Children-Swartz Formula [41]. |
| 2.   | Albuminuria | A high concentration of Albumin was observed in patients with Fabry disease [42]. |
| 3.   | Cystatin –C | Cystatin-cis the potent inhibitor act as a protease inhibitor found in all nucleated cells and is useful for the diagnosis of early-onset that is classical renal dysfunction diagnosis. It can decrease the GFR to a little extent in both males and females [43]. |
| 4.   | Urine microscopy | Phase-contrast microscope-Tubular epithelial cells were seen, Polarized microscope-Urine sediments observation showed Maltese cross bodies encapsulated in the mulberry cells [42]. |
| 5.   | Renal biopsy | Renal biopsy(histological study)is the most trustable tool, Stereomicroscopy- For more sensitive histological renal structures stereomicroscope is used, Electron Microscopy-Zebra bodies (small osmophilic structures) were observed which were seen encased in a coated membrane [42]. |
| 6.   | Proteinuria | Amiloride has an important function in vitro to reduce podocyte (renal cells) motility and it causes proteinuria in mice [43]. |

Table 7. Potential diagnostic tools

| S.No. | Analysis (mi RNA analysis) | Observation |
|-------|---------------------------|-------------|
| 1.    | Transcriptomics | mi RNA analysis shows mi R 29 and mi R 200 detected from the expression of urine mi RNA can cause renal fibrosis before the visibility of signs of albuminuria [44,45]. |
| 2.    | Epigenomics | Fabry patient’s nephropathy from urine sample determination by comparing with control revealed the presence of a greater number of post-translational modifications such as GB3 methylated isoforms found in urine and plasma of the patient [46]. |
| 3.    | Proteomics | Proteinuria cannot be treated as such even after treatment and cause loss of GFR (<60mL/min/1.73m²) [47], The study of proteomics is quite easy in patients with Fabry disease because of its noninvasiveness, and no limit on the number of samples to be used [48]. |
| 4.    | Metabolomics | Male individuals have a higher amount of metabolites in urine samples as gender influences Urine level in pediatric patients [49]. |
5.4 Potential Biomarker

- **Bikunin**: Bikunin is the Urine Protease inhibitor (serine protease). Bikunin was found elevated in the Fabry patients compared to the individuals with other renal impairment. The elevated bikunin along with proteinuria is used as a novel biomarker [50] (Fig. 4).

- **Urine Podocyte**: As the glomerular impairment progresses in Fabry patients, the podocytes enter into urine and resulting in an elevated concentration of urine podocytes. The latter condition is known as podocytinuria (Fig. 4) [2].

- **Pelvic cyst**: Renal impairment correlates with the pelvic cyst reported by regular monitoring with ultrasonography. It is not the only pathognomic or significant tool for Fabry diagnosis but their presence can recruit further diagnosis for Fabry (Fig. 4) [3].

- **Tubular Protein**: Type IV collagen and Transferrin protein leakage has been reported in correlation with GFR and their presence in urine may be considered as the novelty for the diagnostic approach (Fig. 4) [4].

- **Glomerular Protein**: Alpha 1 Microglobulin and N-Acetyl-beta-Glucosaminidase and Alanine aminopeptidase are the glomerular proteins and their dysfunction can be indicated as the sign of Fabry renal impairment (Fig. 4) [5].

**Differential DNA Methylation**: Differential DNA Methylation is also a potential characteristic for rare diseases to detect renal anagenesis, glomerular disease, proteinuria, and membranous nephropathy (Fig. 4) [6].

6. TREATMENT

6.1 Systemic mRNA (Messenger RNA) Therapy

From the preclinical studies, it was revealed that intravenous administration of human GLA encoding systemic mRNA helps to promote the production of the alpha-galactosidase enzyme in mice and humans. It was found thermostable and capable of substrate reduction (accumulated GB3 reduction) as an alpha-galactosidase enzyme in Fabry patients who lack wild-type alpha-galactosidase enzyme. This approach is
also advisable for use in other lysosomal storage disorders [51].

6.2 Enzyme Replacement Therapy

Enzyme replacement therapy (ERT) has been in practice since 2001, which implies the introduction of recombinant GLA into the host (Fabry patient) once in two weeks intravenously. It can revert the abnormalities and metabolic dysfunctionalities [52]. ERT is a costly procedure and requires a lot of skill, most effective in the treatment of people with cardiac and renal Fabry disease at classical onset, however, its non-classical/later-onset effect is not known [52]. Regular administration is required as these enzyme does not have a significant half-life [53].

The two major enzymes are used for enzyme replacement therapy-

1. Agalsidase -alpha “Replagal” (Shire Human Genetic Therapies, Cambridge, A) - 0.2 mg/kg administration in each infusion.
2. Agalsidase-beta “Fabrazyme”, (Genzyme Corporation, Cambridge, MA) - 1 mg/kg administration in each infusion [54]

The FDA (Food and drug administration the USA) has approved only the use of Fabrazyme for ERT [54].

6.3 Chaperone Therapy

Frustaci et al. performed the first clinical trial as pharmacological chaperon therapy using galactose [55]. In Europe and Canada the approval was given to the pharmacological migalastat (Galafold™; Amicus Therapeutics, Cranbury, NJ, USA) for treatment of Fabry disease caused due to amenable mutation [56].

During the study of misfolding mutation in the enzyme, to enhance the intracellular activity of mutant enzyme the competitive inhibitor application (results in the proper folding of mutant enzyme, protein maturation as well as transportation to the lysosomal) approach is applied to treat Fabry disease strictly with misfolding mutant enzyme [57].

1-Deoxygalactonojirimycin (DGJ) is the competitive inhibitor of the potent alpha-galactosidase enzyme that binds to the active site of the enzyme and causes its proper folding as well as intracellular targeting to the lysosome for the degradation of accumulated GB3 in mammals. It has been proved during the study of transgenic mice with the similar alpha-galactosidase enzyme (misfolding mutant) by oral administration [58]. Seventy-eight misfolding mutations have been treated with this approach, some of them are assayed with patient’s cells - A20P, N34S, R49L, F113L, Y207C [59] andR49C, M51K, I91T [60].

6.4 Substrate Reduction Therapy

SRT maintenance therapy requires less dependency on enzyme infusion consequently, it shows excellence in improvement in the quality of life as it circumvents ERT (Enzyme replacement therapy) [61].

![Fig. 5. Methodologies of fabry treatment](image-url)
In-vivo study in a mouse model with early neonatal death indistinguishably showed GB3 accumulation in kidney and vasculature due to lack of an alpha-galactosidase enzyme in Fabry patients. Lymphoblasts were transformed from Fabry disease patients with EtDO-P4 showed a significant reduction of glucocerebroside and globo triaosylceramide.\(^{61}\) Sanne J. van der Veen, et.al.,). In vivo assay of two mouse models with early neonatal death had been studied- 1. Conduritol _ epoxide(CBE)-induced mouse model of neuronopathic GD; 2. Genetic 4L C model. GENZ-682452 and GZ/SAR402671 have been identified under clinical process for the treatment of Fabry disease and in both the model, mouse showed enhancement in survivability with an accumulation of both compounds\(^ {61}\).

6.5 Second-Generation Therapy

Pegunigalsidase-alfa: Cells of tobacco plant produces Pegunigalsidase-alfa (PRX-102) which was modified as fusogen (PEG) polyelethylene glycol for maintenance of stability and to tolerate reduction from clearance was confirmed by experiment on Human plasma. The murine model showed an extra reduction in the GB3 level as compared to an alpha-galactosidase enzyme with the help of PRX 102 in plasma of Fabry patients\(^ {62}\).

Moss-aGal: R- αGAL’s, a plant-derived form is a moss a Gal having immense potential of enzyme activity, and it has the property to be absorbed by endothelial cells. Moss aGal has higher enzymatic activity than alpha-galactosidase as revealed from the studies performed on the FD mice model\(^ {63}\) and is much more effective for clearing accumulated GB3 than alpha-galactosidase. In a single infusion, moss aGal has a half-life of 14 minutes in plasma as detected by pharmacokinetics, less than normal alpha-galactosidase enzyme\(^ {61}\). (Fig. 5).

7. CONCLUSION

Clinical heterogeneity of Fabry Disease endorses the individualized diagnostic approach discovery with transcriptomics, epigenomics, metabolomics based on the patient’s age, gender, type of mutation, and the onset of manifestation. The diagnostic tools utilize oxidative stress biomarkers, elevated GB3, some novel biomarkers like bikunin, tubular and glomerular cellular concentration, urine podocytes, cystatin C, and hold potential promise for Fabry diagnosis and will further expand in foreseeable with several mutations in GLA gene. The classical ERT(Enzyme Replacement Therapy), Chaperone therapy and recently mRNA-based therapy, substrate reduction therapy, second-generation therapy like Pegunigalsidase-alfa, Moss-aGal have the most significant clinical benefits. The conundrums of rarity summarize the need for progressive research and development.

CONSENT

It is not applicable.

ETHICAL APPROVAL

It is not applicable.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Brady RO, Gal AE, Bradley RM, Martensson E, Warshaw AL, Laster L. Enzymatic defect in Fabry's disease. Ceramidetrihexosidase deficiency. \textit{N Engl J Med.} 1967;276(21):1163-1167. DOI: 10.1056/NEJM196705252762101
2. Fall B, Scott CR, Mauer M, Shankland S, Pippin J, Jererson JA, et al. Urinary podocyte loss is increased in patients with Fabry disease and correlates with clinical severity of Fabry nephropathy. \textit{PLoS ONE}. 2016;11: e0168346.
3. Eleonora Riccio, Massimo Sabbatini, Ivana Capuano, Antonio Pisani Early biomarker of fabry nephropathy. \textit{Nephron}. 2019;143:274–281
4. Aguiar P, Azevedo O, Pinto R, Marino J, Baker R, Cardoso C, et al. New biomarkers defining a novel early stage of Fabry nephropathy: A diagnostic test study. \textit{Mol Genet Metab.} 2017;121(2): 162–9
5. Katie Kerr, Helen McAneney, Cheryl Flanagan, Alexander P. Maxwell, and Amy Jayne McKnight.Differential methylation as a diagnostic biomarker of rare renal diseases: a systematic review. Kerr et al. \textit{BMC Nephrology}. 2019;20:320.
6. Fabry disease present as an autoimmune rheumatic disease. Hannah J, Sangle S,
Mehta A, Ginsberg L, Investigators FOS. Natural history of the cerebrovascular complications of Fabry disease. Acta Paediatr. 2005;94(Suppl 447):24–7.

Sweeley CC, Klionsky B. Fabry's Disease: Classification as a sphingolipidosis and partial characterization of a novel glycolipid. J Biol Chem. 1963;238:3148-3150.

Eng CM, Ashley GA, Burgert TS, Enriquez AL, D'Souza M, Desnick RJ. Fabry disease: Thirty-five mutations in the alpha-galactosidase A gene in patients with classic and variant phenotypes. Mol Med. 1997;3(3):174-182.

Eng CM, Resnick-Silverman LA, Niehaus DJ, Astrin KH, Desnick RJ. Nature and frequency of mutations in the alpha-galactosidase A gene that causes Fabry disease. Am J Hum Genet. 1993;53(6):1186-97.

Germain, D.P. Fabry disease. Orphanet J Rare Dis. 2010;5(30). Available: https://doi.org/10.1186/1750-1172-5-30

Banton, Mary H, Raphael Schiffmann, Sharda G. Sabnis, Gary J. Murray, Jane M. Quirk, Gheona Altarescu, and Lev Goldfarb et al. Natural History Of Fabry Renal Disease. Medicine. 2002;81(2):122-138. DOI: 10.1097/0005792-200203000-00003

Desnick RJ, Allen KY, Desnick SJ, Raman MK, Bernlohr RW, Krivit W. Fabry's disease: enzymatic diagnosis of hemizygotes and heterozygotes. Alpha-galactosidase activities in plasma, serum, urine, and leukocytes. J Lab Clin Med. 1973;81(2):157-171.

Schiffmann R, Fuller M, Clarke LA, Aerts JM. Is it Fabry disease? Genet Med. 2016;18(12):1181-1185. DOI: 10.1038/gim.2016.55

Linhart A, Kampmann C, Zamorano JL, et al. Cardiac manifestations of Anderson-Fabry disease: results from the international Fabry outcome survey. Eur Heart J. 2007;28(10):1228-1235. DOI: 10.1093/eurheartj/ehm153

Bernstein HS, Bishop DF, Astrin KH, Konreich R, Eng CM, Nakamura H, Desnick RJ. Fabry disease: Six gene rearrangements and an exonic point mutation in the alpha-galactosidase gene. J Clin Invest. 1989;83(4):1390-9. DOI: 10.1172/JCI114027

The 1000 Genomes Project Consortium. An integrated map of genetic variation from 1,092 human genomes. Nature 491. 2012;50-56. Available:https://doi.org/10.1038/nature11632

Lane DA, Fernhoff PM. Diagnosis of Fabry disease via analysis of family history. J Genet Couns. 2008;17(1):79-83. DOI: 10.1007/s10897-007-9128-x

Iemolo F, Pizzo F, Albegiani G, et al. De novo mutation in a male patient with Fabry disease: A case report. BMC Res Notes. 2014;7(11). Available:https://doi.org/10.1186/1756-0500-7-11

Calabrese Esteban, Botta Guillermo, Rosenfeld Dra. New mutation in Fabry disease: c.44delG, first phenotypic description. Molecular Genetics and Metabolism Reports. 2021;27. DOI: 10.1016/j.ymgmr.2021.100708

Serebrinsky G, et al. Late-onset variants in Fabry disease: Results in high-risk population screenings in Argentina. Molecular genetics and metabolism report. 2015;4:19-24. DOI: 10.1016/j.ymgmr.2015.05.006

Li P, Zhang L, Zhao N, Xiong Q, Zhou Y-A, Wu C, and Xiao. A Novel Alpha-Galactosidase A Splicing Mutation Predisposes to Fabry Disease. Front. Genet. 2019;10:60

Nampoothiri S, Yesodharan D, Bhattacharjee A, Ahamed H, Puri RD, et al. Fabry disease in India: A multicenter study of the clinical and mutation spectrum in 54 patients. JIMD Reports.2020;56:82-94.

Leinenkugel P, Michel S, Conzelmann E, Sandhoff K. Quantitative correlation between the residual activity of beta-hexosaminidase A and arylsulfatase A and the severity of the resulting lysosomal storage disease. Hum Genet. 1992;88(5):513-523. DOI: 10.1007/BF00219337

Shen YC, He ZC, Cai RL, Pan JZ, Wang XM, Li J. Zhonghua Xue Ye Xue Za Zhi. Effect of alpha-galactosidase a deficiency on FV Leiden fibrin deposition and thrombosis in mice. 2009;30(3):162-165.

Lenders M, Karabul N, Dunning T, et al. Thromboembolic events in Fabry disease
and the impact of factor V Leiden. Neurology. 2015;84:1009–1016.
27. Rasmus Bo Hasselbalc, Per Lav Madsen, Henning Bundgaard and JulianeTheilade. Presymptomatic diagnosis of Fabry's disease: a case report”. Journal of Medical Case Reports. 2016;10:330
28. Thadhni R, Wolfe, West ML, et al. Patients with Fabry disease on dialysis in the United States”. Kidney Int. 2002;61:249–255
29. Frank Breunig, Frank Weidemann, Meinrad Beer, Andreas Eggert, Vera Krane, Matthias Spindler, Jo RN Sandstedt, Jo. RG Strothmann, Christoph Wanner. Fabry disease: Diagnosis and treatment. Kidney International. 2003;63(Supplement 84);S181–S185.
30. Nowak A, Mechtler T, Kasper DC, Desnick RJ. Correlation of Lyso-Gb3 levels in dried blood spots and sera from patients with classic and Later-Onset Fabry disease. Molecular Genetics and Metabolism. 2017;121:320–324.
31. Sanchez-Niño MD, et al. Lyso-Gb3 activates Notch1 in human podocytes. Hum. Mol. Genet. 2015; ddv291. Available:https://doi.org/10.1093/hmg/ddv291
32. Slaats GG, Braun F, Hoehne M, et al. Urine-derived cells: a promising diagnostic tool in Fabry disease patients. Science Report.2018;8:11042 . Available:https://doi.org/10.1038/s41598-018-29240-w
33. Simoncini C, Torri S, Montano V, et al. Oxidative stress biomarkers in Fabry disease: Is there a room for them?. J Neurol. 2020;267(12):3741-3752. DOI: 10.1007/s00415-020-10044-w
34. Biancini GB, Vanzin CS, Rodrigues DB, Deon M, Ribas GS, Barschak AG et. al.; “Globotriaosylceramide is correlated with oxidative stress and inflammation in Fabry patients treated with enzyme replacement therapy. Biochim Biophys Acta. 2012;1822(2):226–232.
35. Simoncini C, Chico L, Concolino D, Sestito S, Fancellu L, Boadu W, et Al. Mitochondrial DNA haplogroups may influence Fabry disease phenotype. Neurosci Lett. 2016;629:59–61.
36. Biancini GB, Jacques CE, Hammerschmidt T, de Souza HM, Donida B, Deon M e.t.al.; Biomolecules damage and redox status abnormalities in Fabry patients before and during enzyme replacement therapy. Clin Chim Acta. 2016;461:41–46.
37. Ravarotto V, Carraro G, Pagnin E, BertoldiG, Simioni F, Maiolino G .et.al. Oxidative stress and the altered reaction to it in Fabry disease: A possible target for cardiovascular-renal remodeling?. PLoS One. 2018;13(9):e0204618.
38. Riccio E, Sabbatini M, Buzzese D, Annichiarico Petruzzelli L, Pellegrino A, Spinelli L, et al. Glomerular hyperfiltration: An early marker of nephropathy in Fabry disease. Nephron. 2019;141:10–17.
39. Ramaswami U, Najafian B, Schieppati A, Mauer M, Bichet DG. Assessment of renal pathology and dysfunction in pediatric patients with Fabry disease. Clin. J. Am. Soc. Nephrol. 2010;5:365–370.
40. Levey AS, Stevens LA, Schmid CH, Zhang Y, Castro AF, Feldman HI, et al. A new equation to estimate glomerular filtration rate. Ann. Intern. Med. 2009;150:604–612.
41. Schwartz GJ, Muñoz A, Schneider MF, Mak RH, Kaskel F, Warady BA, Furth SL. New equations to estimate GFR in children with CKD. J. Am. Soc. Nephrol. 2009;20:629–637.
42. Tina Levstek, Bojan Vujkovac, Katarina Trebusak Podkrajsek. Biomarkers of Fabry Nephropathy: Review and Future Perspective. Genes. 2020;11;1091.
43. Zhang B, Xie S, Shi W, Yang Y. Amiloride off-target effect inhibits podocyteurokinase receptor expression and reduces proteinuria, Nephrology Dialysis Transplantation. 2012;27:1746–1755.
44. Jauretche S, Perez GR, Venera G. High Lyso-Gb3 plasma levels associated with decreased miR-29 and miR-200 urinary excretion in a young non-albuminuric male patient with classic Fabry disease. Case Rep.Nephrol. 2019; 4980942.
45. Jauretche S, Venera G, Antongiovanni N, Perretta F, Perez GR. Urinary excretion of microRNAs in young Fabry disease patients with mild or absent nephropathy. Open J. Nephrol. 2018;8:71–83.
46. About M, Boutin M, Lavole P, Auray-Blais C. Tandem mass spectrometry multiplex analysis of methylated and non-methylated urinary Gb3 isoforms in Fabry disease patients. Clin. Chim. Acta. 2016;452:191–198.
47. Schi mann R, Hughes DA, Linthorst GE, Ortiz A, Svarstad E, Warnock DG, West
ML, Wanner, C. Screening, diagnosis, and management of patients with Fabry disease: Conclusions from a Kidney Disease: Improving Global Outcomes (KDIGO) Controversies Conference. Kidney Int. 2017;91:284–293.

54. Schi_mann R, Waldek S, Benigni A, Auray-Blais C. Biomarkers of Fabry disease nephropathy. Clin. J. Am. Soc. Nephrol. 2010;5:360–364.

55. Schi_mann R, Waldek S, Benigni A, Auray-Blais C. Biomarkers of Fabry disease nephropathy. Clin. J. Am. Soc. Nephrol. 2010;5:360–364.

56. KDIGO, Clinical practice guideline for the evaluation and management of chronic kidney disease, Kidney Int. 2012,2013; Suppl 3:1–150.

57. Fan JQ, Ishii S, Asano N, Suzuki Y. Accelerated transport and maturation of lysosomal-galactosidase A in Fabry lymphoblasts by an enzyme inhibitor. Nat. Med. 1999;5:112–115.

58. Satoshi ISHII. Pharmacological chaperone therapy for Fabry disease. The Japan Academy; 2012. DOI: 10.2183/pjab.88.18

59. Benjamin ER, Flanagan JJ, Schilling A, Chang HH, Agarwal L, Katz E, et al. The pharmacological chaperone1-deoxygalactonojirimycin increases alpha-galactosidase A levels in Fabry patient cell lines. J. Inherit. Metab. Dis. 2009;32:424–440.

60. Shin SH, Kluepfel-Stahl S, Cooney AM, Kanesi CR, Quirk JM, Schiffmann R, Brady RO, Murray GJ. Prediction of the response of mutated-galactosidase A toa pharmacological chaperone. Pharmacogenet. Genomics. 2008;18:773–780.

61. Sanne J. van der Veen, Carla E. M. Hollak, André B. P. van Kuilenburg, Mirjam Langeveld. Developments in the treatment of Fabry disease. J Inherit Metab Dis. 2020;43:908–921.

62. Schiffmann R, Goker-Alpan O, Holida M, et al. Pegunigalsidasealfa, a novel PEGylated enzyme replacement therapy for Fabry disease, provides sustained plasma concentrations and favorable pharmacodynamics: A 1-year phase ½ clinical trial. J Inherit Metab Dis. 2019;3:534-544.

63. Shen JS, Busch A, Day TS, et al. Mannose receptor-mediated delivery of moss-made alpha-galactosidase and efficiently correct enzyme deficiency in Fabry mice. J Inherit Metab Dis. 2016;2:293-303.