Stargardt macular dystrophy and therapeutic approaches

Kaoru Fujinami 1,2,3, Nadia Waheed 4, Yannik Laich 3,5, Paul Yang 6, Yu Fujinami-Yokokawa 1,2,7, Joseph J Higgins 8, Jonathan T Lu 8, Darin Curtiss 9, Cathryn Clary 8, Michel Michaelides 2,3

ABSTRACT

Stargardt macular dystrophy (Stargardt disease; STGD1; OMIM: 248200) is the most prevalent inherited macular dystrophy. STGD1 is an autosomal recessive disorder caused by multiple pathogenic sequence variants in the large ABCA4 gene (OMIM: 601691). Major advances in understanding both the clinical and molecular features, as well as the underlying pathophysiology, have culminated in many completed, ongoing and planned human clinical trials of novel therapies. The aims of this concise review are to describe (1) the detailed phenotypic and genotypic characteristics of the disease, multimodal imaging findings, natural history of the disease, and pathogenesis, (2) the multiple avenues of research and therapeutic intervention, including pharmacological, cellular therapies and diverse types of genetic therapies that have either been investigated or are under investigation and (3) the exciting novel therapeutic approaches on the translational horizon that aim to treat STGD1 by replacing the entire 6.8 kb ABCA4 open reading frame.

INTRODUCTION

Stargardt macular dystrophy or Stargardt disease (STGD1; OMIM: 248200) is one of the most common macular dystrophies.1-8 STGD1 was first described by Karl Stargardt in 1909 and is characterised by bilateral progressive loss of visual acuity (VA) and central vision.9 There are three presentations of STGD1, childhood onset, adulthood onset and late onset, with earlier presentation being associated with a worse prognosis.10-20

STGD1 typically presents with a variable degree of macular atrophy and yellow-white flecks at the level of the retinal pigment epithelium (RPE) (figure 1).5 10 11 14 21 However, there are a broad range of manifestations resulting in a large spectrum of clinical presentations, onset, progression, psychophysical and electrophysiological findings, as well as variable prognosis.6-13 15-20 22-32

The global prevalence of STGD1 has been estimated at 1 per 6578.33 Due to the progressive nature and often early onset of STGD1, patients typically face long-term health-related financial, emotional and psychological implications. Although information on the economic burden of STGD1 alone is not available, these impacts have been studied in a broad range of inherited retinal diseases (IRDs).34 Some studies estimate the total cost is over US$27.5 billion per year among people aged 40 years and younger with eye disorders.35 36

In 1997, disease-causing sequence variants in the ABCA4 (ATP binding cassette subfamily A member 4; OMIM: 601691) gene were identified as the cause of STGD137; with more than 2000 variants found to date. The carrier frequency for a disease-causing variant in ABCA4 may be as high as 1:20, although the true prevalence of retinopathy attributed to ABCA4 variants is likely much higher than that of STGD1, given it can also cause other phenotypes including cone dystrophy, cone-rod dystrophy and rod-cone dystrophy.38 Moreover, the bone spicule pigmentation of ABCA4-associated retinopathy attributed to severe cone-rod dystrophy (formerly retinitis pigmentosa inversa) is now widely accepted as a sign of late-stage cone-rod dystrophy and peripheral degeneration, rather than rod-cone dystrophy.39

An increasing amount of research on the clinical and molecular genetics of STGD1/ABCA4 has been performed over the past 15 years. This has facilitated a growing understanding of the underlying pathophysiology, which has resulted in both completed and ongoing trials, as well as a broad range of planned clinical trials.6 7 40-42 Many types of interventions have been explored to treat STGD1, including pharmacological treatments, regenerative cell therapies43 44 and gene replacement/supplementation therapy.45 46 Increasingly, precision medicine focusing on particular variants and mechanisms has been gaining attention (including gene editing).7 42-47

The aim of this review is to describe the phenotypic and genotypic characteristics, imaging findings, natural history and pathogenesis of the disease. Additionally, the characteristics of particular ABCA4 variants, a pathogenicity assessment and a concise overview of the therapeutic landscape—past, present and future—will be presented.

DISEASE OVERVIEW

Gene family/gene function

The ABCA4 gene is a large, highly polymorphic gene with an estimated size of 6819 bp encoding a 2273-amino acid protein, including 50 exons.35 ABCA4, formerly described as ABCR, is a member of the ABC transporter gene superfamily, encoding the retinal-specific transmembrane protein, a member of the ATP-binding cassette transporter superfamily.48 ABCA4 contains two transmembrane domains, two...
glycosylated extracellular domains and two nucleotide-binding domains (figure 2A).3 6 48

ABCA4 is localised along the rim of the rod/cone outer segment discs and is involved in the active transport of retinoids from photoreceptor to RPE in the retinoid cycle.48–51 The visual/retinoid cycle involves a series of enzyme-catalysed reactions that convert all-trans retinal, generated with photobleaching of rhodopsin/cone opsins, back to 11-cis retinal.48 50–53 All-trans retinal is released from the light-activated rhodopsin/cone opsins into the rod/cone outer segments to form a complex with phosphorylcholine (PE), resulting in N-retinaldehyde–PE.48 54 This complex is then actively transported to the disc surface by ABCA4 (figure 2B,C). ABCA4 has also been shown to be expressed at lower levels in the RPE, where it may serve a similar function for the recycling of retinaldehyde.54

Molecular genetics

The vast allelic heterogeneity of ABCA4 is clearly demonstrated by the number of reported sequence variations (>2000) to date, resulting in macular dystrophy, cone dystrophy, cone–rod and rod–cone dystrophy.3 6 48 Due to this heterogeneity, establishing genotype–phenotype correlations is highly challenging. Likewise, the identification of ABCA4 genetic characteristics related to intronic variants remains largely elusive, despite genetic sequencing advances. Deep intronic variants have been shown to significantly account for the missing heritability in STGD1 and have been associated with late-onset disease and mild phenotype.55–57 However, due to the highly polymorphic nature of the ABCA4 gene, the genetic and pathogenic features of deep intronic variants remain difficult to characterise.

Null variants or variants predicted to be more deleterious are generally associated with earlier onset disease and characterised by a more severe, rapidly progressive phenotype, often with more generalised retinal involvement.6 8 11–13 16 25 26 32 Milder variants, such as missense variants, are often associated with later onset disease, typically milder, more slowly progressive and more likely isolated to the macula.58 Although certain missense variants can produce severe functional effects similar to nulls (eg, p.Leu541Pro/p.Ala1038Val (complex), p.Glu1022Lys, p.Cys1490Tyr, p.Glu1087Lys, p.Thr1526Met, p.Arg1640Trp and p.Cys2150Tyr/p.Cys2150Tyr).13 16 25 26 58 The interaction between the variants (including disease-causing and benign variants) may also affect function.59 Nevertheless, certain missense variants, including p.Arg2030Gln, are commonly observed in the mildest ABCA4-associated phenotype, late-onset/foveal sparing STGD1 (FS-STGD1).14 26

While ABCA4 allelic heterogeneity is high, there are founder variants associated with STGD1 in various racial and ethnic groups as well as differences in clinical features related to ABCA4-retinopathy.6 There have been larger cohort STGD1 studies featuring the genotypic profile and phenotypic correlations for the White populations in European/North American, although there is a limited number of studies for the Latin, Asian, African and other populations.3 11 12 18 20 32 40 61 However, further studies are required to better understand the clinical difference and effects across different ethnic and racial groups.

A category of rare hypomorphic alleles has also been characterised, which are typically observed in milder phenotypes with better prognosis.54 Lee et al showed that these hypomorphic variants can modulate the severity of the phenotype irrespective of the severity of the allele in trans.54 Notably, the mechanism of hypomorphic alleles or milder variants has been attributed to either reduced function of the ABCA4 protein produced in normal amounts (ie, missense variants) or reduced production of a normal functioning protein (ie, splice variants). The aberrant splicing in the ABCA4 gene and resulting variants, whose pathogenicity was previously unknown, has more recently been reclassified as pathogenic based on mid-gene and fibroblast assays.53 64

Molecular mechanisms

Failure of transport due to ABCA4 dysfunction or mislocalisation leads to the inefficient removal of N-ret-PE from photoreceptor outer segments, resulting in an accumulation of bisretinoid compounds in the outer segment discs and ultimately in toxic levels of bisretinoid A2PE in photoreceptor membranes.48 49 A2PE is hydrolysed to form the highly toxic metabolite N-retinylidene-N-retinyl-ethanolamine (A2E), which accumulates as a major component of lipofuscin in RPE cells, and ultimately causes RPE dysfunction and death, with subsequent photoreceptor dysfunction/loss (figure 2D).53

Previous studies of STGD1 mouse models (ie, ABCA4 knockout) support the aforementioned pathogenesis; however, there are limitations such as lack of a macula in mice and the mild phenotype in mouse models showing a later-onset disease with slower degeneration than that of typical patients with STGD1.51 65 Moreover, there is data from multimodal high-resolution imaging studies in humans that in some cases photoreceptor cell loss may precede RPE cell dysfunction/loss.17 19 20 66 67

Clinical aspects

Patients with STGD1 commonly present with progressive bilateral central vision loss. The onset is often in the first or second decades of life.11 12 24 The onset relates to the disease severity; an earlier onset disease is associated with more deleterious variants compared with adult-onset disease, which is more frequently due to missense variants.11–14 16 25–27

Comprehensive investigations are crucial for clinical diagnosis and monitoring, including fundus photography, fundus autofluorescence (FAF) imaging, spectral-domain optical coherence tomography (SD-OCT) and electrophysiological assessment.1 3 6 7 Likewise, clinical classifications are useful to assess the disease severity associated with a particular genotype group.11 12 19 20 23 25 32

At an early stage, ophthalmoscopy can reveal a normal retina or minimal retinal abnormalities, including foveal reflex abnormality, white macular dots and RPE disturbance, with or without vision loss.13–17 Retinal imaging with FAF, SD-OCT and electrophysiological assessment (including pattern, full-field and multifocal electroretinograms; PERG, FFERG, mfERG) are useful for diagnosis.42 68–70 Notably, children with STGD1 may not have retinal flecks on funduscopy or FAF at the early stage, but over time may develop these flecks associated with increasing macular atrophy.13 15–16 In very early childhood-onset disease with relatively preserved vision, macular atrophy involves the paraviewe and spares the fovea, and these changes are preceded by fine, symmetrical, yellowish-white dots at the central macula in some cases and/or characteristic loss of outer nuclear layer transparency on SD-OCT.13–17

Electrophysiological assessment is particularly helpful in providing better-informed advice on prognosis.11 A classification of three functional phenotypes based on electrophysiological findings is well-established: group 1—severe PERG abnormality (macular dysfunction) with normal FFERGs; group 2—severe PERG abnormality with additional generalised cone dysfunction on FFERGs and group 3—severe PERG abnormality with additional generalised cone and rod dysfunction on FFERGs.11 22 A
Figure 1  Representative cases of Stargardt disease (STGD1). Typical findings of Stargardt disease (STGD1; A–C). Fundus photograph of the right eye showing macular atrophy with yellow-white flecks at the level of the retinal pigment epithelium (RPE; A). Fundus autofluorescence (FAF) imaging identified an area of decreased autofluorescence (DAF) at the macula and multiple surrounding foci of abnormal AF (B). Spectral-domain optical coherence tomography (SD-OCT) demonstrated marked loss of outer retinal layers and RPE at the macula, with multiple hyper-reflective foci corresponding to flecks (C). A broad range of FAF patterns and progression over time in STGD1 are presented, with corresponding fundus photographs (D–T). FAF pattern can be classified into three types based on the area(s) of DAF and the background features (heterogeneous or homogeneous): type 1 (Baseline; F) to type 2 (follow-up; G), type 1 (baseline; J) to type 2 (follow-up; K), type 2 (baseline; M) to type 2 (follow-up; N), type 2 (baseline; P) to type 3 (follow-up; Q), type 3 (baseline; S) to type 3 (follow-up; T). Genetic information (ABCA4, Transcript ID: NM_000350.3; ENST00000370225.4): Case 1 (top row; : c.4139C>T, p.Pro1380Leu. Case 2 (second row; D–G): c.3322C>T, p.Arg1108Cys; c.6079C>T, p.Leu2027Phe. Case 3 (third row; H–K): c.768G>T; c.2588G>C, p.Gly863Ala. Case 4 (fourth row; I–N): Unavailable. Case 5 (fifth row; O–Q): c.1622T>C, p.Leu541Pro; c.3113C>T, p.Ala1038Val; c.617_618delCG, p.Ser206ArgfsTer320. Case 6 (bottom row; R–T): c.5461–10T>C. *Permission to reuse the figure for publication in the journal has been obtained by the licensed content publisher, Springer Nature (Number: 5415100406042; License date: 23 October 2022).
longitudinal ERG study has confirmed the prognostic implications of the aforementioned ERG groups, with group 1 having the best prognosis; group 2 having an intermediate or variable prognosis; and group 3 having the worst prognosis.

All patients with initial rod ERG involvement demonstrated clinically significant electrophysiological deterioration; whereas, only 20% of patients with normal FFERGs at baseline showed clinically significant progression over time. These findings are supported by the association with genotype grouping (e.g., group 3 is associated with a greater prevalence of null variants), and are also relevant in the design, patient selection and monitoring of potential therapeutic interventions.

STGD1 with a later age of onset has been increasingly recognised. Patients with late-onset STGD1 often develop the FS phenotype (FS-STGD1). SD-OCT often exhibits outer retinal tubulation at the edge of atrophy, suggesting that the primary site of degeneration of this phenotype is the RPE and choroid. On the other hand, patients with foveal atrophy can manifest photoreceptor cell loss at the fovea at the early stage. Therefore, the presence of two distinct phenotypes—non-FS-STGD1, which is primarily childhood-onset and adulthood-onset STGD1, and FS-STGD1—suggests more than one disease mechanism in ABCA4-associated retinopathy. The fact that a different distribution of disease-causing variants exists between these two phenotypes appears to support this hypothesis.

Figure 2  Molecular mechanisms of STGD1 (ABCA4-retinopathy) a schematic of ABCA4 protein structure (A), the visual cycle (B), transport (C) and failure of transport leading to retinal degeneration (D). The ABCA4 gene transcribes a large retina-specific ABCA4 protein with two transmembrane domains (TMD), two glycosylated extracellular domains (ECD) and two nucleotide-binding domains (NBD) (A). All-trans retinal is released from the light-activated rhodopsin/cone opsin into the rod/cone outer segments (B) to form a complex with phosphatidylethanolamine (PE), resulting in N-ret-PE, then this complex is actively transported to the disc surface by ABCA4 (C). Failure of this transport results in accelerated deposition of a major lipofuscin fluorophore (A2E) in the RPE, which causes RPE dysfunction and cell death, with subsequent photoreceptor cell loss over time (D).
Natural history

Natural history studies play a key role in advancing understanding of disease progression. Over the past 8 years, multicentre, international, large-cohort studies (≥250 subjects) have been conducted: the retrospective and prospective Natural History of the Progression of Atrophy Secondary to Stargardt Disease (ProgStar) studies. The aims were to characterise the natural history and identify sensitive, reliable and clinically relevant outcome measures, which could be employed in clinical trials. Here, we focus on FAF, given it has been prioritised in clinical trial endpoints to date.

In a ProgStar retrospective study of a subset of 224 eyes (mean age, 33.0±15.1 years), the total mean area of definitely decreased autofluorescence (DDAF) at the first visit was 2.6 mm², and the mean progression of DDAF was 0.51 mm²/year. In a prospective study with 12 months of observation, the mean area of DDAF at baseline was 3.93 mm², and the estimated progression of DDAF was 0.76 mm²/year. The rate of progression was dependent on the initial size of the lesion in both studies, as previously reported by other longitudinal studies.

FAF imaging may serve as a monitoring tool for interventional clinical trials that aim to slow anatomical disease progression. Lesion size at baseline appears to be a strong predicting factor for lesion growth and can be partially accounted for by square root transformation.

Studies using en face SD-OCT and OCT angiography (OCTA) have shown that the area of photoreceptor ellipsoid zone (EZ) loss was 1.6-fold greater than the area of RPE atrophy, which suggests that photoreceptor degeneration may precede RPE loss in STGD1. Moreover, OCTA showed that choriocapillaris vascular density was abnormal even beyond the areas of photoreceptor EZ and RPE loss, supporting a complex chorioreti
cular pathophysiology due to ABCA4 dysfunction. These findings may also be useful for developing end points in clinical trials.

THERAPEUTIC APPROACHES

Although there are currently no proven cures for STGD1, there are multiple treatment avenues being investigated. In addition to retinal prosthesis, there are clinical trials of pharmacological agents, stem cell therapy and genetic therapies (see summary in table 1).

Pharmacological therapies are arguably the most advanced and closest to potential approval as meaningful treatments.

Pharmacological therapy

Several pharmacological agents have been specifically developed that target different aspects of the retinoid cycle and are potentially beneficial in slowing or preventing progression in STGD (figure 3A), with some studies also reporting improvements in retinal and/or visual function (table 1).

The aims of these agents are either (1) lowering the formation of toxic products of the retinoid cycle by reducing delivery of vitamin A or inhibition of various enzymes participating in the cycle, including drugs such as emixustat, ALK-001, LBS-008, STG-001, fenretinide and A1120; or (2) directly targeting toxic metabolites such as A2E or pathways activated by these metabolites (eg, the complement cascade), including soraprazan and Avacincaptad pegol.

These drugs aim to impede formation of A2E and lipofuscin by either slowing the rate of vitamin A dimerisation (ALK-001), enhancing lipofuscin removal (soraprazan), imposing competitive inhibitory mechanisms on the retinal binding protein-4 (LBS-008 (tinlareban), STG-001, fenretinide, vutrisiran and A1120), or modulating the activity of RPE65 (emixustat).

Many of these drugs have been or are currently in phase 1/2 or 3 trials (LBS-008: NCT03735810, emixustat: NCT03772665 and NCT03033108, ALK-001: NCT02402660) (table 1). Avacincaptad pegol, a complement C5 inhibitor, is also being investigated in a phase 2 trial (NCT03364153). Additional pharmacotherapeutic agents directly or indirectly targeting the visual cycle have been developed, including the complement-mediated response to accumulated by-products of the visual cycle.

Cellular therapies

For the management of advanced disease, cell replacement strategies offer potential benefit. A phase 1/2 clinical trial (NCT01469832) of human embryonic stem cell (hESC)-derived RPE cells for treating severe advanced STGD1 has been completed. Findings from the UK site of this trial identified subretinal hyperpigmentation consistent with the survival of viable transplanted hESC-derived RPE cells. Borderline improvements in VA were noted in 4 of 12 patients; however, microperimetry did not demonstrate evidence of functional benefit at 12 months. A phase 1 clinical trial testing the long-term safety and tolerability of hESC-derived RPE (NCT01625559) showed no adverse events, with favourable results. Further trials are anticipated, including evaluation of combined RPE and photoreceptor transplants, which are either derived from hESCs or induced pluripotent stem cells (iPSC).

Trials involving autologous bone marrow-derived stem cells (BMSC; NCT01920867, NCT03011541, NCT03772938) are at various stages of completion. One study (NCT01920867) showed improvement in 61.8% of the eyes treated, with 76.9% of patients exhibiting VA improvement. Other studies involving BMSC treatment (NCT03772938, NCT03011541) are still active with no results yet reported.

Genetic therapies

Gene replacement therapy has been increasingly applied to photoreceptor diseases, aiming to slow or prevent further degeneration and/or improve function in early to intermediate stage disease. Preclinical studies in gene replacement showing phenotypic improvement in abca4−/− mice have subsequently encouraged the development of human gene therapy trials. Adeno-associated virus (AAV) vectors have been the leading choice for gene delivery in human gene therapy; however, the AAV capsids exhibit limited cargo capacity. The ABCA4 gene is far larger than the current AAV vector capacity. Considering the larger cargo capacity of lentiviruses, subretinal injection of a lentiviral vector delivering ABCA4 (SAR422459) was developed. The StarGen phase I/II trial for this therapy (NCT01367444) was terminated early, with a longer-term follow-up study ongoing (NCT01736592). Although there were no safety concerns in either of these trials, there was no evidence of visual improvement.

Optogenetics represents a genetic therapy for advanced disease, where residual non-photoreceptor cells are made light sensitive by using AAV to deliver often an opsin-related photopigment. This approach is being explored in a Phase II clinical trial in STGD1, with AA02 carrying a multicharacteristic opsin gene expression cassette (NCT05417126).

Future treatment options

In addition to treatments currently undergoing clinical trials, there are several therapeutic approaches on the horizon for...
Table 1  Summary of therapeutic trials for Stargardt disease (STGD1; ABCA4 retinopathy)

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Treatment</th>
<th>Route</th>
<th>Phase/Phase Follow-up</th>
<th>ClinicalTrials.gov identifier</th>
<th>Title</th>
<th>Summary results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inhibition of vitamin A dimerisation</td>
<td>ALK-001</td>
<td>Oral</td>
<td>Phase 2/long-term</td>
<td>NCT02439625</td>
<td>Open-Label Extension: Tolerability and Effects of ALK-001 on Stargardt Disease</td>
<td>Active study</td>
</tr>
<tr>
<td>Inhibition of vitamin A dimerisation</td>
<td>ALK-001</td>
<td>Oral</td>
<td>Phase 2</td>
<td>NCT012402660</td>
<td>Phase 2 Tolerability and Effects of ALK-001 on Stargardt Disease</td>
<td>Reduction in growth rate of atrophic lesions, no change in BCVA, no reports of night blindness or impaired dark adaptation</td>
</tr>
<tr>
<td>Inhibition of vitamin A dimerisation</td>
<td>ALK-001</td>
<td>Oral</td>
<td>Phase 1</td>
<td>NCT02230228</td>
<td>Phase 1 Safety Study of ALK-001 in Healthy Volunteers</td>
<td></td>
</tr>
<tr>
<td>RBP4 inhibition</td>
<td>STG-001</td>
<td>Oral</td>
<td>Phase 2</td>
<td>NCT01449551</td>
<td>Study of STG-001 in Subjects With Stargardt Disease</td>
<td>Reported AEs: 6 patients low dose: 1 dry eye, 1 subretinal fluid, 1 skin disorder; 4 patients high dose: 1 chromatopsia, 1 delayed dark adaptation, 2 night blindness, 1 visual impairment, 1 dry skin</td>
</tr>
<tr>
<td>RBP4 inhibition</td>
<td>Tinlarebant</td>
<td>Oral</td>
<td>Phase 3</td>
<td>NCT05244304</td>
<td>Study to Evaluate the Safety and Efficacy of Tinlarebant in the Treatment of Stargardt Disease in Adolescent Subjects Lesion(s) in Adolescent Subjects With STGD1</td>
<td>Active study</td>
</tr>
<tr>
<td>RBP4 inhibition</td>
<td>Vutrisiran</td>
<td>Subcutaneous</td>
<td>Phase 3</td>
<td>Not yet registered</td>
<td>THEIA-A: A Phase 3 Global, Randomised, Double-Blinded, Placebo-Controlled Study to Evaluate the Clinical Outcomes, Efficacy and Safety of Vutrisiran in Patients with Stargardt Disease Type 1 (STGD1)</td>
<td>Upcoming trial</td>
</tr>
<tr>
<td>Inhibition of visual cycle (RPPE65)</td>
<td>Emixustat</td>
<td>Oral</td>
<td>Phase 3</td>
<td>NCT03772665</td>
<td>Safety and Efficacy of Emixustat in Stargardt Disease</td>
<td>No meaningful differences between treatment groups regarding macular atrophy</td>
</tr>
<tr>
<td>Inhibition of visual cycle (RPPE65)</td>
<td>Emixustat</td>
<td>Oral</td>
<td>Phase 2</td>
<td>NCT03033108</td>
<td>Pharmacodynamic Study of Emixustat Hydrochloride in Subjects With Macular Atrophy Secondary to Stargardt Disease</td>
<td>Dose-dependent suppression of rod b-wave amplitude recovery post photobleaching, confirming emixustat’s biological activity: AE: dark adaptation (11/23, 47.8%), erythropsia (5/23, 21.7%), vision blurred (4/23, 17.4%), photophobia (3/23, 13%), visual impairment (3/23, 13%), headache (2/23)</td>
</tr>
<tr>
<td>Inhibition of visual cycle</td>
<td>4-Methylpyrazole</td>
<td>Intravenous</td>
<td>Phase 1</td>
<td>NCT00346853</td>
<td>Phase 1 Pilot Study of 4-MP to Treat Stargardt Macular Dystrophy</td>
<td>No effect on dark adaptation in healthy probands, further studies suspended because substance doesn’t seem to inhibit the visual cycle strong enough</td>
</tr>
<tr>
<td>Removal of lipofuscin</td>
<td>Soraprazan</td>
<td>Oral</td>
<td>Phase 2</td>
<td>EudraCT 2018-001496-20</td>
<td>A multinational, multi-centre, double-masked, placebo-controlled proof of concept trial to evaluate the safety and efficacy of oral soraprazan in Stargardt disease</td>
<td>Active study</td>
</tr>
<tr>
<td>Induce Autophagy</td>
<td>Metformin</td>
<td>Oral</td>
<td>Phase 1</td>
<td>NCT04545736</td>
<td>Oral Metformin for Treatment of ABCA4 Retinopathy</td>
<td>Active study</td>
</tr>
<tr>
<td>Inhibition of complement C5</td>
<td>Zimura</td>
<td>Intravitreal</td>
<td>Phase 2</td>
<td>NCT03364153</td>
<td>Zimura Compared With Sham in Patients With Autosomal Recessive Stargardt Disease (STGD1)</td>
<td>Active study</td>
</tr>
<tr>
<td>Supplements</td>
<td>Omega-3 Fatty Acids</td>
<td>Oral</td>
<td>Phase 1</td>
<td>NCT03297515</td>
<td>Therapeutic Potential of Omega-3 Fatty Acids Supplementation in Dry Macular Degeneration and Stargardt Disease</td>
<td>Increase of BCVA in the active group after 24 weeks, score of a questionnaire on perceived vision and subjective mood higher in the active group at week 24, CAVE: patient cohort Stargardt+dry AMD, results not shown separately</td>
</tr>
<tr>
<td>Supplements</td>
<td>Docosahexaenoic acid (DHA)</td>
<td>Oral</td>
<td>Phase 1</td>
<td>NCT00420602</td>
<td>DHA Supplementation in Patients With STGD3</td>
<td>No beneficial effect over 8 years, poor compliance</td>
</tr>
<tr>
<td>Supplements</td>
<td>DHA</td>
<td>Oral</td>
<td>Phase 1</td>
<td>NCT00060749</td>
<td>Effect of DHA Supplements on Macular Function in Patients With Stargardt Macular Dystrophy and Stargardt-like Macular Dystrophy</td>
<td>No effect on macular function</td>
</tr>
<tr>
<td>Supplements</td>
<td>Saffron</td>
<td>Oral</td>
<td>Phase 1</td>
<td>NCT01278227</td>
<td>Saffron Supplementation in Stargardt’s Disease</td>
<td>Short-term supplementation was well tolerated and had no detrimental effects on the electroretinographic responses of the central retina</td>
</tr>
<tr>
<td>Gene therapy (ABCA4)</td>
<td>SAR422459</td>
<td>Subretinal</td>
<td>Phase 1/Phase 2 Follow-up</td>
<td>NCT01236592</td>
<td>Phase VII Follow-up Study of SAR422459 in Patients With Stargardt’s Macular Degeneration</td>
<td>Treatment was well tolerated. No clinically significant changes in visual function tests were found to be attributable to the treatment. Reduction of flecks in one eye. 1 case of ocular hypertension. 27% of treated eyes showed exacerbation of retinal pigment epithelium atrophy on FAE</td>
</tr>
<tr>
<td>Gene therapy (ABCA4)</td>
<td>SAR422459</td>
<td>Subretinal</td>
<td>Phase 1</td>
<td>NCT01367444</td>
<td>Phase IIIA Study of SAR422459 in Participants With Stargardt’s Macular Degeneration</td>
<td>Favorable safety profile</td>
</tr>
<tr>
<td>Optogenetics</td>
<td>vMCO-010</td>
<td>Intravitreal</td>
<td>Phase 2</td>
<td>NCT05417126</td>
<td>Safety and Effects of a Single Intravitreal Injection of vMCO-010 Optogenetic Therapy in Subjects With Stargardt Disease</td>
<td>Active study</td>
</tr>
</tbody>
</table>
I/II clinical trials for the use of AON-application of AON-Usher syndrome (NCT05085964) were conducted, but two of (NCT03140969, NCT03913130), retinitis pigmentosa and intravitreal 2024; et al 108 mentioned above, there are fundamental limitations to using therapy systems that use alternative delivery vectors. As STGD1.93 Anti- patients that carry one of the ABCA4 exhibited great potential for the personalised treatment of Mechanism Treatment Route Phase ClinicalTrials.gov identifier Title Summary results

Stem cells hESC Derived RPE (MA09-HRPE) Subretinal Phase 2 Follow-up NCT02941991 A Follow-up Study to Determine the Safety and Tolerability of Sub-retinal Transplantation of Human Embryonic Stem Cell Derived Retinal Pigmented Epithelial (hESC-RPE) Cells in Patients With Stargardt's Macular Dystrophy (SMD) Active study

Stem cells hESC Derived RPE (MA09-HRPE) Subretinal Phase 1 Phase 2 NCT01135006 Sub-retinal Transplantation of hESC Derived RPE Cells in Patients With Stargardt's Macular Dystrophy No evidence of adverse proliferation, rejection, or serious ocular or systemic safety issues related to the transplanted tissue. 1318 px (72%) had patches of increasing subretinal pigmentation. BCVA improved in ten eyes, improved or remained the same in seven eyes, and decreased by more than ten letters in one eye, no similar improvements in untreated FE. Vision-related quality-of-life measures increased 3–12 months after transplantation.

Stem cells hESC Derived RPE (MA09-HRPE) Subretinal Follow-up NCT02445612 Long Term Follow-up of Sub-retinal Transplantation of hESC Derived RPE Cells in Stargardt Macular Dystrophy Patients Focal areas of subretinal hyperpigmentation, no evidence of uncontrolled proliferation or inflammatory responses. No meaningful improvements in BCVA, no benefit in micropachy of 12 months, one case of localised retinal thinning and reduced sensitivity in the area of hyperpigmentation. No significant change in participant-reported quality of life.

Stem cells hESC Derived RPE (MA09-HRPE) Subretinal Phase 1 Phase 2 NCT01469832 Safety and Tolerability of Sub-retinal Transplantation of hESC-RPE Cells in Patients With SMD No serious AEs occurred throughout the 3 year period following the injection of hESC-RPE cells. The functional and anatomical results were favourable, compared with the natural course of SMD reported in the ProgStar study.

Stem cells hESC Derived RPE (MA09-HRPE) Subretinal Phase 1 Phase 2 NCT01625559 A Phase I, Open-Label, Prospective Study to Determine the Safety and Tolerability of Sub-retinal Transplantation of hESC-RPE (MA09-HRPE) Cells in Patients With SMD No serious AEs occurred throughout the 3 year period following the injection of hESC-RPE cells. The functional and anatomical results were favourable, compared with the natural course of SMD reported in the ProgStar study.

Stem cells hESC Derived RPE (MA09-HRPE) Subretinal Phase 1 Phase 2 NCT02749734 Clinical Study of Subretinal Transplantation of Human Embryo Stem Cell Derived Retinal Pigment Epitheliums in Treatment of Macular Degeneration Diseases Active study

Stem cells hESC Derived RPE subretinal Phase 1 Phase 2 NCT02903576 Stem Cell Therapy for Outer Retinal Degenerations (sub retinal injections vs hESC RPE seeded on a polymeric substrate implanted in the subretinal space) Active study

Stem cells Autologous bone marrow-isolated stem/progenitor cells Intravitreal Phase 1 NCT03772938 Stem Cells Therapy in Degenerative Diseases of the Retina No results from STGD group to date

Stem cells Autologous bone marrow derived stem cells (BMSC) Retrobulbar, subtenon, intravitreal, intracocular, subretinal and intravenous Phase 1 NCT03011541 Stem Cell Ophthalmology Treatment (SCOT) Study II Active study

Stem cells Autologous BMSC Retrobulbar, subtenon, intravitreal, intracocular, subretinal and intravenous NCT01920867 Stem Cell Ophthalmology Treatment Study 21/34 eyes (61.8%) improved, 8/34 eyes (23.5%) remained stable, and 5/34 eyes (14.7%) showed continued progression. The average central vision improvement following treatment was 17.96% and ranged up to 80.5%. Of 17 patients treated, 13/17 px (76.5%) showed visual acuity improvement in one or both eyes, 31/7px (17.6%) showed no net loss, and 1px worsened as a consequence of disease progression; 94.1% of patients had improved vision or remained stable. There were no AEs.

AE, adverse event; AMD, age-related macular degeneration; BCVA, best-corrected VA; FAE, fundus autofluorescence; VA, visual acuity.

STGD1. 93 Anti-sense oligonucleotide (AON) treatments have exhibited great potential for the personalised treatment of patients that carry one of the ABCA4 splice variants. 93 97 Phase I/II clinical trials for the use of an AON-based therapeutic intravitreal injection to treat Leber congenital amaurosis (NCT03140969, NCT03913130), retinitis pigmentosa and Usher syndrome (NCT05085964) were conducted, but two of these studies (NCT03913130, NCT05085964) were terminated early for reasons unrelated to safety. Research involving the application of AON-based therapy has recently shown promise at preventing further deterioration in Stargardt disease models. 94 Other therapeutic methods being explored include gene therapy systems that use alternative delivery vectors. As mentioned above, there are fundamental limitations to using AAVs in STGD1, principally cargo capacity, as well as concerns about immune reactions to the viral vector itself. 95 96 Thus, future treatment methodologies that employ non-viral vectors—such as cationic lipids and lipid nanoparticles (LNPs)—would be potentially safer than viral vector options with respect to the absence of immunogenic viral proteins. LNPs have also shown robust capability to condense and deliver various nucleic acid molecules up to several million nucleotides, 97 while concurrently protecting the DNA/RNA cargo from unknown chromosomal position effects. 98 99 However, the level of expression and transfection efficiency for non-viral vectors is typically much lower than viral vectors. Recent strategies such as PEylation of LNPs or use of a pH-sensitive amino lipid have been shown to markedly enhance efficiency and targeting of ocular delivery. 100 101

Table 1 Continued

Mechanism Treatment Route Phase ClinicalTrials.gov identifier Title Summary results

Stem cells hESC Derived RPE (MA09-HRPE) Subretinal Phase 2 Follow-up NCT02941991 A Follow-up Study to Determine the Safety and Tolerability of Sub-retinal Transplantation of Human Embryonic Stem Cell Derived Retinal Pigmented Epithelial (hESC-RPE) Cells in Patients With Stargardt's Macular Dystrophy (SMD) Active study

Stem cells hESC Derived RPE (MA09-HRPE) Subretinal Phase 1 Phase 2 NCT01135006 Sub-retinal Transplantation of hESC Derived RPE Cells in Patients With Stargardt's Macular Dystrophy No evidence of adverse proliferation, rejection, or serious ocular or systemic safety issues related to the transplanted tissue. 1318 px (72%) had patches of increasing subretinal pigmentation. BCVA improved in ten eyes, improved or remained the same in seven eyes, and decreased by more than ten letters in one eye, no similar improvements in untreated FE. Vision-related quality-of-life measures increased 3–12 months after transplantation.

Stem cells hESC Derived RPE (MA09-HRPE) Subretinal Follow-up NCT02445612 Long Term Follow-up of Sub-retinal Transplantation of hESC Derived RPE Cells in Stargardt Macular Dystrophy Patients Focal areas of subretinal hyperpigmentation, no evidence of uncontrolled proliferation or inflammatory responses. No meaningful improvements in BCVA, no benefit in micropachy of 12 months, one case of localised retinal thinning and reduced sensitivity in the area of hyperpigmentation. No significant change in participant-reported quality of life.

Stem cells hESC Derived RPE (MA09-HRPE) Subretinal Phase 1 Phase 2 NCT01469832 Safety and Tolerability of Sub-retinal Transplantation of hESC-RPE Cells in Patients With SMD No serious AEs occurred throughout the 3 year period following the injection of hESC-RPE cells. The functional and anatomical results were favourable, compared with the natural course of SMD reported in the ProgStar study.

Stem cells hESC Derived RPE (MA09-HRPE) Subretinal Phase 1 Phase 2 NCT01625559 A Phase I, Open-Label, Prospective Study to Determine the Safety and Tolerability of Sub-retinal Transplantation of hESC-RPE (MA09-HRPE) Cells in Patients With SMD No serious AEs occurred throughout the 3 year period following the injection of hESC-RPE cells. The functional and anatomical results were favourable, compared with the natural course of SMD reported in the ProgStar study.

Stem cells hESC Derived RPE (MA09-HRPE) Subretinal Phase 1 Phase 2 NCT02749734 Clinical Study of Subretinal Transplantation of Human Embryo Stem Cell Derived Retinal Pigment Epitheliums in Treatment of Macular Degeneration Diseases Active study

Stem cells hESC Derived RPE subretinal Phase 1 Phase 2 NCT02903576 Stem Cell Therapy for Outer Retinal Degenerations (sub retinal injections vs hESC RPE seeded on a polymeric substrate implanted in the subretinal space) Active study

Stem cells Autologous bone marrow-isolated stem/progenitor cells Intravitreal Phase 1 NCT03772938 Stem Cells Therapy in Degenerative Diseases of the Retina No results from STGD group to date

Stem cells Autologous bone marrow derived stem cells (BMSC) Retrobulbar, subtenon, intravitreal, intracocular, subretinal and intravenous Phase 1 NCT03011541 Stem Cell Ophthalmology Treatment (SCOT) Study II Active study

Stem cells Autologous BMSC Retrobulbar, subtenon, intravitreal, intracocular, subretinal and intravenous NCT01920867 Stem Cell Ophthalmology Treatment Study 21/34 eyes (61.8%) improved, 8/34 eyes (23.5%) remained stable, and 5/34 eyes (14.7%) showed continued progression. The average central vision improvement following treatment was 17.96% and ranged up to 80.5%. Of 17 patients treated, 13/17 px (76.5%) showed visual acuity improvement in one or both eyes, 31/7px (17.6%) showed no net loss, and 1px worsened as a consequence of disease progression; 94.1% of patients had improved vision or remained stable. There were no AEs.
Figure 3  Current and future treatment agents for STGD1 A schematic showing (A) current pharmacological STGD1 treatment agents and (B) novel genetic therapies for STGD1. (A) Schematic showing the normal visual cycle (pink) and failure of transport due to ABCA4 dysfunction (blue). Agents (RPE65 inhibitors, deuterated Vitamin A, RBP4 antagonists) lower the formation of toxic products of the retinoid cycle by enzymatic inhibition, reducing delivery of vitamin A, or antagonising the retinoid binding protein 4 (RBP4). (B) Schematic showing non-integrating episomal and integrating nuclear gene therapies. The ABCA4 gene is expressed in retinal photoreceptors and the transporter is localised at the rim of rod and cone photoreceptors at the outer segment (OS), which connects to the inner segment (IS) via connecting cilium (CC). To target disordered transport due to ABCA4 dysfunction, adeno-associated virus (AAV) therapies deliver the large 6.4 kb ABCA4 gene (>4.7 kb AAV cargo limit) to the nucleus by splicing together fragments of the ABCA4 gene, wherein the transgene remains in an episomal state. Gene editing therapies cut or alter single nucleotide(s) within the ABCA4 gene via techniques such as CRISPR-Cas, which targets specific variants. Gene coding replaces the entire ABCA4 gene via an engineered transposase, enabling its application to all variants, including exonic and intronic nucleotide variants, as well as structural variants.
Other approaches being developed include either using dual or triple AAV vectors to deliver full length ABCA4 to the nucleus by splicing together fragments of the cDNA.102-104

Novel CRISPR-based molecular tools have also emerged as a therapeutic option for STGD1 (figure 3B).103 Recently, gene editing via CRISPR/Cas9 has been employed to correct patho-

genic variants of ABCA4 in human iPSCs (hiPSC) for STGD1 patients.106 However, there are potential safety concerns associ-

ated with gene editing methods being developed for STGD1, namely the introduction of double-stranded breaks (DSBs) in the genome during editing. Gene editing systems such as CRISPR/Cas9 create DSBs, which run the risk of triggering error-prone endogenous DNA repair mechanisms that could otherwise cause unwanted effects.107 108 However, systems that exploit

transposon-based mutagenesis—such as fish-derived Sleeping Beauty109 110—and insect-derived PiggyBac111—may circumvent this issue. A potential drawback for such methods is that the DNA recognition sequence may be found throughout the human genome and thus the gene would not be targeted to a specific site. Thus, an ideal transposon-based system would be one that is mammal-derived and absent of immunogenic effects, with the capability to insert genetic material of unlimited size at a site-specific genomic target.

By combining features of the above systems, there is potent-

tial for developing much needed novel gene therapy techniques that can transport a larger size DNA cargo (and avoid the introduc-

tion of DSBs) for STGD1 and other common IRDs such as

USH2A-associated retinitis pigmentosa and Usher syndrome. For example, a novel DNA integrating platform developed by

SalioGen Therapeutics—Gene Coding—combines many of the above-mentioned features (figure 3B). The technology uses a tissue-specific and cell-specific nanoparticle (NP) to co-encap-

sulate mRNA encoding a synthetic bioengineered, mammalian transposase and a DNA element containing the gene of interest for a specific disease target. Notably, the DNA element can contain large genetic cargos, such as ABCA4, or a combina-

tion of several genetic factors, since the NP does not have size limitations.

Several potential benefits of this type of technology are currently under investigation. First, NPs that target specific cell types such as photoreceptors and RPE are being developed.112 Second, the NP capability to deliver large gene cargos is being exploited to deliver single or multiple genetic components and regulatory elements to control gene expression. Third, the non-viral nature of the DNA integration system may decrease the immunogenicity seen with viral delivery systems. Finally, in contrast to AAV therapies and non-viral gene editing tech-

nologies and gene therapies, the transposase avoids unwanted genomic effects by avoiding DSBs113 while integrating ther-

apeutic genes at polynucleotide sites in the genome. All of these potential attributes may be important in treating degenerative retinal disorders such as STGD1, which is caused by multiple pathogenic variants in large genes.

CONCLUSIONS
STGD1 is one of the most common IRDs, presenting in childhood, early adulthood and in later life. This ABCA4-associated retinopathy is highly heterogeneous both clinically and geneti-

cally. The deep clinical and genetic characterisation that has been undertaken over the last 15 years has improved understanding of underlying disease mechanisms, natural history and outcome metrics, allowing multiple therapeutic trials to be conducted. Further trials are anticipated, including pharmaceutical in the immediate term, with innovations towards the development of novel gene therapy approaches on the horizon.

Author affiliations
1Laboratory of Visual Physiology, Division of Vision Research, National Institute of
Sensory Organs, NHO Tokyo Medical Center, Meguro-ku, Tokyo, Japan
2Institute of Ophthalmology, University College London, London, UK
3Moorfields Eye Hospital NHS Foundation Trust, London, UK
4Department of Ophthalmology, Tufts University School of Medicine, Boston, Massachusetts, USA
5Eye Center, Medical University of Freiburg Faculty of Medicine, Freiburg, Germany
6Oregon Health and Science University Casey Eye Institute, Portland, Oregon, USA
7Department of Health Policy and Management, Keio University School of Medicine
Graduate School of Medicine, Shinjuku-ku, Tokyo, Japan
8SalioGen Therapeutics Inc, Lexington, Massachusetts, USA
9Applied Genetic Technologies Corporation, Alachua, Florida, USA

Twitter Darin Curtis @PharmerD

Acknowledgements The authors wish to acknowledge Yu Fujinami-Yokokawa for assistance with figure preparation and Kathryn Verhoeven for editorial support during manuscript preparation.

Contributors Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; KF, NW, YL, PY, YF-Y, JJH, JTL, DC, CC and MM. Drafting the work or revising it critically for important intellectual content; KF, NW, YL, PY, YF-Y, JJH, JTL, DC, CC and MM. Final approval of the version to be submitted; KF, NW, YL, PY, YF-Y, JJH, JTL, DC, CC and MM. Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved; KF, NW, YL, PY, YF-Y, JJH, JTL, DC, CC and MM.

Funding KF, MM, YL and YF-Y are supported by grants from the National Institute for Health Research Biomedical Research Centre at Moorfields Eye Hospital NHS Foundation Trust and UCL Institute of Ophthalmology. MM is supported by the Wellcome Trust 2 (099173/2/12/2). NW is supported by funding from Tufts University School of Medicine. PY is supported by Foundation Fighting Blindness TRAP1 Award TA-NMT-0521-0803-OHSU-TRAP. Grant P30 EY01572 from the National Institutes of Health (Bethesda, MD), the Malcolm M. Marquis, MD Endowed Fund for Innovation, and unrestricted departmental funding from Research to Prevent Blindness (New York, NY). DC is a full-time employee of AGTC. JJH and JTL are full-time employees of SalioGen Therapeutics.


Therapeutics, a shareholder in Ocuudyne, and a previous shareholder of Gypsyoc Therapeutics. JJH, JTL and CC: JJH are currently full-time employees and stock option holders of SalioGen Therapeutics. C Clary is a former employee of SalioGen Therapeutics. DC: D Curtis is a full-time employee and stock option holder of AGTC. YF-Y, YF-Y and YF-Y have no conflicts of interest to disclose. MM: Consultant (category C): Acucela, MeiraGTx, Janssen, Stargazer, Claris Bio, SalioGen Therapeutics, Bello Bio and Aylumyn. MM holds equity in MeiraGTx.

Patient consent for publication Not applicable.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement No data are available.

Open access This is an open access article distributed in accordance with the Creative Commons Attribution 4.0 Unported (CC BY 4.0) license, which permits others to copy, redistribute, remix, transform and build upon this work for any purpose, provided the original work is properly cited, a link to the license is given, and indication of whether changes were made. See: https://creativecommons.org/licenses/by/4.0/.

ORCID iDs
Kaoru Fujinami http://orcid.org/0000-0003-4248-0033
Cathryn Clary
http://orcid.org/0000-0003-0634-7593

Yu Fujinami-

504

Bu

26

24

22

20

19

15

13

11


