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Herpes simplex keratitis: A brief clinical overview

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Abstract

The aim of our minireview is to provide a brief overview of the diagnosis, clinical aspects, treatment options, management, and current literature available regarding herpes simplex keratitis (HSK). This type of corneal viral infection is caused by the herpes simplex virus (HSV), which can affect several tissues, including the cornea. One significant aspect of HSK is its potential to cause recurrent episodes of inflammation and damage to the cornea. After the initial infection, the HSV can establish a latent infection in the trigeminal ganglion, a nerve cluster near the eye. The virus may remain dormant for extended periods. Periodic reactivation of the virus can occur, leading to recurrent episodes of HSK. Factors triggering reactivation include stress, illness, immunosuppression, or trauma. Recurrent episodes can manifest in different clinical patterns, ranging from mild epithelial involvement to more severe stromal or endothelial disease. The severity and frequency of recurrences vary among individuals. Severe cases of HSK, especially those involving the stroma and leading to scarring, can result in vision impairment or even blindness in extreme cases. The cornea's clarity is crucial for good vision, and scarring can compromise this, potentially leading to visual impairment. The management of HSK involves not only treating acute episodes but also implementing long-term strategies to prevent recurrences and attempt repairs of corneal nerve endings *via* neurotization. Antiviral medications, such as oral Acyclovir or topical Ganciclovir, may be prescribed for prophylaxis.

The immune response to the virus can contribute to corneal damage. Inflammation, caused by the body's attempt to control the infection, may inadvertently harm the corneal tissues. Clinicians should be informed about triggers and advised on measures to minimize the risk of reactivation. In summary, the recurrent nature of HSK underscores the importance of both acute and long-term management strategies to preserve corneal health and maintain optimal visual function.

Key Words: Herpes simplex virus; Herpes simplex keratitis; Acyclovir; Neurotization; Reactivation

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Core Tip: Our minireview is based on herpes simplex keratitis. This type of corneal viral infection is caused by the herpes simplex virus (HSV), which can affect several tissues, including the cornea and deeper uvea. Its ability to remain dormant for extended periods and reactivate with serious morbid ocular presentation makes it an important pathogen to be reviewed. The body's immune response to HSV is another potential cause of herpes simplex keratitis. Clinical management is short-term and long-term to prevent reactivation. Clinicians should be informed about triggers and advised on measures to minimize the risk of reactivation.

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INTRODUCTION

The eye is the organ of sight responsible for collecting and converting visual stimuli for onward transmission to the brain. The cornea, specifically, was believed to have full 'ocular immune privilege'[1] but recent studies challenged this submission[2]. Infectious keratitis ranks fifth among the leading causes of severe visual impairment globally[3]. Microbial keratitis can be bacterial, fungal, or viral/protozoal[4,5]. Viruses are implicated in up to 4/5th of all conjunctivitis in humans[6]. Herpes simplex virus (HSV) is the most common ocular disease-causing viral agent[7-9]. Ocular HSV infection can affect various local tissues[10]. Corneal manifestations of HSV-1 are termed Herpes simplex keratitis (HSK). It often presents with dendritic ulceration and eventual corneal scarring[11].

Systemic conditions like diabetes are not known to exacerbate HSK[12]. Dendritic corneal epithelial lesions found commonly on eyes infected with HSV, may also be seen in diabetes-associated neurotrophic keratopathy[13,14]. HSK may manifest as only mild keratitis at one end of its spectrum but may potentially result in ulcerative keratitis and perforation at its end stage[15,16]. HSV intrastromal keratitis was more common than epithelial keratitis in large-group studies[17, 18]. The herpes virus may infect an eye as a single infective organism or may occur in a polymicrobial form together with other types of microbes[19-21]. HSV causes diseases around the genitalia (herpes labialis) and the brain (herpes encephalitis)[22].

METHODOLOGY

Published articles in English were sought by searching through the PubMed database and with Reference Citation Analysis (<https://www.referencecitationanalysis.com>) with search net of the past 5 years between 2018 and 2023. Articles without full texts and abstracts were not considered. Also, articles written in other languages, out of the scope of the topic, or deemed unclear in methodology were screened out. The PubMed search query was: "(keratitis, herpetic" [MeSH Terms] OR ("keratitis" [All Fields] AND "herpetic" [All Fields]) OR "herpetic keratitis" [All Fields] OR ("herpes" [All Fields] AND "simplex" [All Fields] AND "keratitis" [All Fields]) OR "herpes simplex keratitis" [All Fields]) AND (2018:2023 [pdat])".

A total of 606 records were returned from the search string and preferred reporting items for systematic reviews and meta-analyses[23] table showing selection criteria is shown below in Figure 1.

UNDERSTANDING THE PATHOGENESIS OF HERPES SIMPLEX KERATITIS

The HSV causes HSK[24], It is among the most ubiquitous human pathogens on earth[25-27]; and a major blinding disease in developed countries[28,29]. It is the second most common cause of corneal scarring according to a large study [30], It has a seroprevalence in the range of 60%-90%[31]. It is also commonly seen in immunocompromised individuals

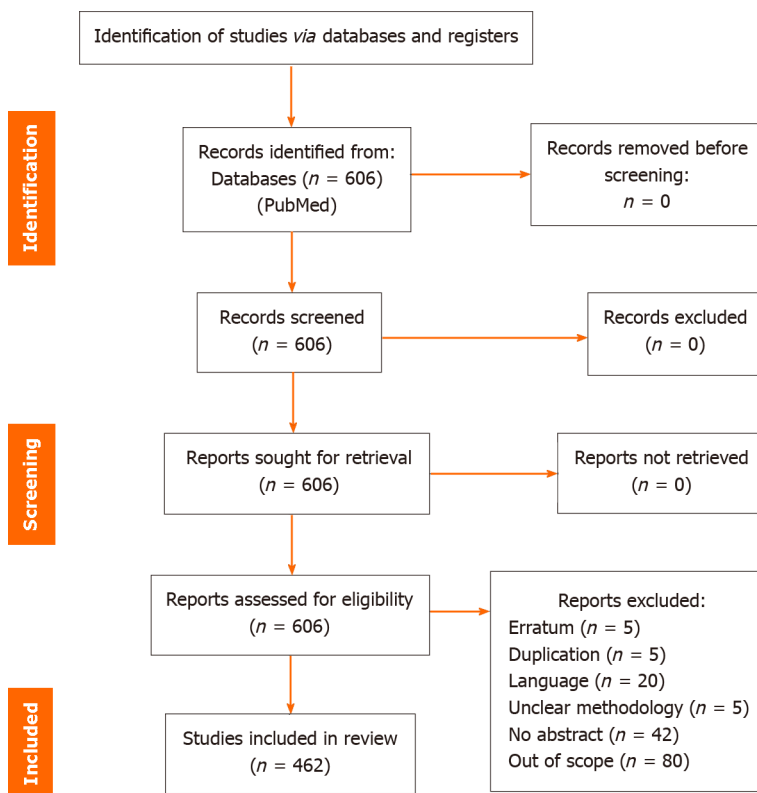


Figure 1 The preferred reporting items for systematic reviews and meta-analyses 2020 table showing review process.

[32]. Multiple strains of the virus present with differing symptomatology according to duration and virulence[33,34]. HSV can deceive toll-like receptors (TLR) which would ordinarily signal the innate immune system to attack the virus[35]. Cui *et al*[36] reported on quantitative proteomics of the infected corneal epithelial cells suggesting that P4HB, ACLY, HSP90AA1, and EIF4A3 proteins are involved in the relationships between hosts and viruses [36]. It is known that HSV-1 infection alters the host metabolism to suit its propagation *in vitro*[37]. Costimulatory molecules like CD80 and CD28 may also reduce the expression of HSV symptoms[38-40].

The virus typically affects humans more than other animals. After initial infection with HSV, hosts carry the infection for life[41-43]. Transmission generally is by direct contact of the skin or mucous membranes with lesions or secretions bearing virions[44,45]. HSV is generally divided into two which include HSV-1 and HSV-2[46,47]. HSV-1 is primarily the cause of infections around the mouth, face, and eyes[48]; while HSV-2 is majorly transmitted sexually and causes genital diseases. HSV-2 could also infect the eyes by contact or spread from lesions present in the genital area. This explains the presence of HSV-2 infection in the eyes of neonates, the route of infection being the mothers' birth canal. This underscores the importance of HSV testing in pregnant women especially those showing signs such as cold sores, and blisters[49]. Biological sex differences do not seem to induce changes in ocular HSV-1 disease expression, as evidenced by BALB/C and C57BL/6 murine models[50,51].

Yadav *et al*[52] documented 10 cases of HSV-2-linked blepharokeratoconjunctivitis over 16 years[52]. HSV-1 typically affects the mucocutaneous distribution of the trigeminal nerve. It usually does not present any symptoms but could sometimes manifest as a nonspecific upper respiratory tract infection. The virus then spreads from the infected epithelial cells to close-by sensory nerve endings and is carried along the nerve axon to the cell body of the trigeminal ganglion. At this level, the virus genome enters the nucleus of a neuron where it stays indefinitely in a dormant state[52,53]. Studies on non-human primates also revealed the persistence of HSV-1 in the ciliary ganglion and cornea during latency[54].

Harrison *et al*[55] hypothesized that stress stimulates viral gene expression and productive infection during reactivation from the latency stage[55]. Yan *et al*[56] also postulated that stress can reactivate a dormant HSV infection [56].

There are typically four subtypes of HSK which include: (1) epithelial keratitis; (2) immune stromal keratitis; (3) stromal necrotic keratitis; and (4) endotheliitis.

This classification depends on the layer of cornea affected; and whether the keratitis is caused by a reactivated or primary infection. The most common subtype is epithelial keratitis which appears as rough granular spots that form punctate lesions on the cornea; they usually coalesce quickly to create the typical dendritic lesions. These dendritic cells typically change in density wildly along the course of herpetic keratitis[57]. Keratic precipitates may also be observed [58]. Shah *et al*[59] reported that stromal keratitis (with no identifiable ulceration) was the most common presentation of HSK[59]. There were reports of both acute & subacute dendritic epithelial keratitis findings following incisional cataract surgeries; and transepithelial photorefractive keratectomy in one patient[60,61]. It is key to differentiate toxic epithelial keratitis following cataract surgery from HSK[62]. HSV geographic corneal epithelial defects increase predisposition to ocular infections *via* fastidious bacteria[63]; and *Stenotrophomonas maltophilia*[64].

An ocular manifestation of HSV specifically in the cornea is termed HSK: Which had a 2016 prevalence of about 1.7 million people worldwide[65]. It is the most prevalent infectious blindness-causing disease in the developed world[66, 67], and is also prevalent in developing countries[68]. HSK commonly occurs monocularly, but can also present binocularly in certain conditions such as HIV and rheumatoid arthritis[69]. HSK has been known to affect all layers of the cornea and can be a cause of interstitial keratitis when the stroma is involved[70]. Whether inherent reports of unilateral posterior interstitial keratitis with hypoesthesia can be wholly attributed to HSK remains unproven[71]. Primary infection of any branch of the trigeminal nerve can cause an inactive infection of nerve cells in the trigeminal ganglion. Without prior ocular HSV infection, a person could still develop HSV keratitis due to the interneuronal spread of HSV within the trigeminal ganglion[72]. While a majority of patients initially present with corneal epithelial inflammation, about a third of them either present with or develop stromal keratitis[73].

Neutrophil and CD4+ mediated mechanisms are involved in the pathogenesis of herpetic stromal keratitis following viral spread along the corneal epithelium[74]. In mouse models of recurrent HSK, corneal sensory nerve retraction and replacement with aberrant sympathetic nerves potentiate pathologic processes with CD4+ T cells post-HSV-1 reactivation [75]. Damage at the level of sensory corneal nerves is termed neurotrophic keratopathy[76,77]. Substance-P (SP) production is largely depleted during the early stage of corneal nerve damage in HSK, followed by increased levels, possibly *via* a positive feedback loop during corneal disease manifestation; this surge of SP binds to neurokinin-1-receptor, upregulating the release of pro-inflammatory cytokines on the ocular surface[78]. Bell's facial nerve palsy reportedly occurred with herpetic stromal keratitis in the case of an immunocompetent individual[79].

Recurrence of HSV infection is widely agreed to be the result of virus reactivation in the trigeminal nerve ganglion; which travels along nerve axons to introduce its genome into the eye and initiate replication using the eye's cellular processes to make new copies of the virus. US-11 protein encoded in HSV-1 may play a role in the pathogenesis of worsening keratitis by promoting the translation of viral amino acids following the reactivation of HSV[80]. There is evidence supporting the presence of latent virus in cornea tissue, this could be the cause of recurrent donor-derived HSV, however, this is still very controversial[81].

Evidence shows the reactivation of HSV among patients using latanoprost in managing glaucoma[82,83]. HSV reactivation has also been linked to local, systemic, and topical steroid medications including the use of intravitreal triamcinolone injection[84]. Narang *et al*[85] further reported a case of reactivation of HSK after bilateral botulinum toxin injection to manage epiphora[85]. Ishimaru *et al*[86] reported that the HSV-1 virus replicated in host tissue partly due to proteasomal degradation of the Ras-GRF2 factor, while also demonstrating that this can be reversed by the proteasome inhibitor MG132[86]. Differentials for HSK include Acanthamoeba, Mycobacterium[87], Nocardia[88], Microsporidia[89] and Arthrographis kalrae keratitis[90]. Dong *et al*[91], identified trauma to be the main cause of infectious keratitis in their study[91]. HSK may also complicate the course of acute retinal necrosis in 20% of sufferers[92-93].

Research has shown that endosomal and cytoplasmic Pattern Recognition Receptors and the cell surface recognize HSV and as such start a cascade of immune response which includes Interferons (IFN), Chemokine, and Cytokine production as well as the recruitment of other inflammatory cells to the location of the infection[94]. IFN-1 release in acute HSV keratitis limits dendritic lesion enlargement[95]. Tripartite motif 21 (TRIM21) proteins reportedly inhibit IFN-beta; increasing the release of more proinflammatory cytokines, *e.g.* interleukin (IL)-6, TNF-alpha[96]. Reactive oxygen species (ROS) release from neutrophils in HSK-infected eyes was hypothesized to be catalyzed by nicotinamide adenine dinucleotide phosphate oxidase 2 enzyme[97]. The protein Osteopontin may also mitigate the inflammatory process observed in ocular HSV inflammation at the risk of also upregulating viral replication[98].

HSV-1-encoded ICP-5 proteins are crucial for capsid reassembly processes during viral replication[99]. Novel studies suggest that the upregulation of tryptophan hydroxylase during viral replication implicates the derangement of serotonin neurotransmitter pathways[99]. Ubiquitination is a process of viral protein modification; its first step is the bonding of ubiquitin to ubiquitin-activating enzyme1; HSV-1 induces bonding of ubiquitin-activating-enzyme 1a isoform with Lys604: Ubiquitination at Lys604 functions as a rate-limiting step of HSV-1 replication[100].

DIAGNOSTIC APPROACHES FOR HERPES SIMPLEX KERATITIS: CHALLENGES AND ADVANCEMENTS

HSK may be diagnosed by its clinical presentation on the slit-lamp biomicroscope[101]. Slit-lamp biomicroscopy provides better sensitivity than other low-resource alternatives[102]. It should be noted that slit-lamp findings in HSV infection are similar to endotheliitis secondary to other Herpesviridae: Cytomegalovirus and varicella zoster[103]. Visually, this diagnosis usually includes dendritic/geographical ulceration[104]. The common presenting symptoms: Photophobia, redness, itching, tearing, irritation, pain, discharge, and watery eyes usually subside after about 2 wk. Pain experienced by HSK sufferers has been likened to post-refractive surgery pain[105]. Deep Learning Artificial Intelligence has been identified as a positive aid in diagnosing HSK, especially in areas with less eye care-related manpower[106-108].

Ancillary Deep Learning methods integrated into clinical practice aided earlier diagnosis of HSK from its differentials [109]. Machine learning-based multinomial regression reduced the frequency of misdiagnosing HSV anterior uveitis from other uveitis etiologies[110]. Optical coherence tomography (OCT) is useful in monitoring patients' reactions to medication therapy[111,112]. Soliman *et al*[113] described the anterior segment-OCT findings of HSK as having sub-epithelial infiltration and specific stromal hyper-reflective patterns. Although these features are not unique to HSK they could help in diagnosing and monitoring HSK[113].

Spectral domain OCT has been used *in vivo* to provide a better understanding of the inflammatory and repair processes involved in HSK. Active HSK shows significant epithelial and stromal thickening while the inactive disease process shows a change in the structure at the site of stromal thinning due to the scarring[114]. Acanthamoeba keratitis (AK) and

HSV-keratitis are mimics[115,116]. Subjective determination of corneal lesion depth *via* anterior segment OCT may distinguish between these pathogens at earlier stages[115]. AK tends to invade the corneal stroma aggressively, causing radial keratoneuritis, in contrast to herpetic keratitis[115].

Diagnosing HSV typically involves identifying the virus or its proteins, HSV-specific antibodies, or HSV genetic materials in the blood[117]. Culture staining is limited as most diagnostic dyes have poor sensitivity to non-bacterial pathogens[118]. As early as 1996, immunofluorescence and polymerase chain reaction were already being used to detect HSV in corneal tissue[119]. Hirota *et al*[120] have reported successful monitoring of HSV levels in tears by using polymerase chain reaction analyses[120].

The conventional strategies for the diagnosis of HSV include serological tests, viral culture, and molecular techniques [121]. Viral culture is done by needle aspiration or the use of a swab and then cultured for a few days before microscopic analysis is carried out to determine HSV cytopathic effects. Viral culturing requires great-quality specimen collection, proper handling, and transportation of the specimen.

Compared to Herpes Zoster ophthalmicus, older age, diabetes mellitus and history of surgery are poor prognostic correlates for HSK[122]. Neonatal herpetic stromal keratitis can be confirmed by polymerase chain reaction (PCR)[123]. Multiplex real-time PCR (RT-PCR) has been found to identify HSV DNA reliably and is ideal in the diagnosis of HSV keratitis in the microbiology laboratory[124]. HSV superinfection can be diagnosed using multiplex PCR[125].

Diagnosing HSK is paramount as other conditions could mimic the typical appearance pattern in the cornea, Chang *et al*[126], showed that antiglaucoma medications could cause pseudo dendritic keratitis which is typically in the center-lower cornea as horizontal linear lesions. Benzalkonium chloride has been implicated in most cases[126]. Haidar *et al* published a case report on the subject of the misdiagnosis of a foreign body as HSK[127].

Research has found that Nocardia keratitis, AK, and intraepithelial neoplasia can be misdiagnosed clinically for HSV infection, correct diagnosis of HSV is paramount as treatment modalities are different for these conditions[128-132]. Atypical microsporidial and fungal keratitis may mimic expected HSV findings from the clinicians' perspective also[133, 134]. Another problem occurs when other microbes superimpose on HSV to cause or exacerbate keratitis[135].

The tear HSV-slgA test has been identified as a technique to identify HSV infection[136]. Diagnosing HSV prenatally has proved difficult as ultrasound results are usually not specific to congenital HSV infection[137].

Quantitative RT-PCR was shown by Mohammadpour *et al*[138], to be an excellent technique for detecting HSK[138] while Tóth *et al*[139] showed that PCR could identify HSV in about every 2.8th patients with a clinical history of HSK[139].

Parekh *et al*[140] have advocated for the use of Shotgun sequencing to analyze samples for the presence of HSK[140]. PCR is not sufficiently reliable in the diagnosis of HSV-induced stromal keratitis and endotheliitis due to limitations associated with assessing diseased corneal tissue specimens; hence, viral etiologies in these cases are often inferred or presumed clinically[141]. Real-time PCR was useful in making differential diagnoses of diffuse HSV endotheliitis with feathery infiltration from fungal keratitis[142].

Tear film analysis *via* quantitative microfluidic PCR yielded good sensitivity for the detection of Herpesviridae in instances of epithelial HSK[143]. Tear film protective analysis identified high concentrations of IL-1A, IL-12B, DEFB4A, and CAMP for eyes infected with HSV epithelial keratitis[144,145]. Polymerase chain reaction and viral culture sensitivity in the diagnosis of HSV is limited, with the sensitivity of viral culturing being 50% and PCR being between 55%-88% while the sensitivity even reduces further in the identification of recurrent HSV disease[146].

HSV-1 DNA, antigens, and Latency-associated Transcript (LAT) in the cornea can prove crucial to the diagnosis of atypical clinical presentations or post-infectious stages where it might be difficult to identify the cause of an innocuous cornea scar[147].

Detection of the HSV LAT gene by reverse transcriptase quantitative PCR is superior to conventional PCR and Immunohistochemistry[148].

Louise and Sotiria reported the use of cornea pachymetry and epithelial thickness maps to provide an objective assessment of stromal inflammation. They reported that pachymetry and corneal thickness maps helped to identify HSV stromal keratitis; differentiating it from less debilitating HSV keratitis, and even neurotrophic keratopathy. It also offered an objective measurement for stromal inflammation resolution[149]. Studies have shown[149] Amplivue to be a rapid, potentially office-based diagnostic test for detecting HSV-1 and 2 as compared to more expensive and time-consuming PCR testing. *In-vivo* confocal microscopy was successfully used to study microscopic changes in cornea structures of feline and canine models with HSK[150].

Metagenomic deep sequencing can help to identify specific nucleic acids in complex ocular samples and assign them to specific organisms, thereby aiding diagnosis[151].

Ferreira *et al*[152] examined records of 235 keratitis patients presenting to a tertiary center between 2007 and 2015. As part of their comparisons and conclusions, HSK negatively correlated with poor outcomes after management[152].

Clinical characteristics of HSV-induced anterior uveitis can mimic other viral and non-infectious uveitis most particularly at the onset of disease. PCR and Goldman-Witmer coefficient should be carried out on aqueous humor samples in suspected viral cases[153].

Danileviciene *et al*[154], identified the role of the *C21orf91* gene in the development of HSK where they described the condition to be 2.9 times more likely in patients with the rs10446073 genotype being more common[154]. According to Borivoje *et al*[155], the CC IL28B gene has been identified to be present in individuals with recurrent HSK[155].

Cornea sensitivity of patients with HSK especially stromal keratitis or those who had suffered before is usually lower; they typically have lower Cornea hysteresis, and lower Corneal resistance factor (CRF). Even the contralateral eyes of patients with previous HSK infection have less CRF and cornea hysteresis[156].

Cornea esthesiometry and Laser scanning confocal microscopy have been shown to reveal a significant decrease in cornea sensitivity and sub-basal nerve fibers: Which recover after around 6 months but never return to normal anatomy [157].

Studies have shown that obese and overweight individuals are more likely to develop recurrent simplex keratitis[158]. The use of corneal impression membranes led to higher detection of HSK compared to swab techniques[159]. Storing HSV-1 inoculated polytetrafluorethylene impression membranes at +35 °C for three months led to a reduction of DNA recovery; storage at +4 °C, -20 °C and -70 °C for 10 d were optimal for HSV-1[160].

Computational bio-sequencing methodology identified HSK and other corneal virulent organisms *in vitro*[161]. Bioinformatics analyses suggest that UL24.5 is a possible determinant of pathogenesis[162] Miyazaki *et al*[163] in their study showed that RAGEs (receptors for Advanced glycation end products) is a sensor of HSV-1 infection, this is a route to possible diagnosis for HSV[163].

ANTIVIRAL THERAPY FOR HERPES SIMPLEX KERATITIS: EFFICACY AND LIMITATIONS

There are lots of anti-viral prescribing patterns currently, Cabrera-Aguas *et al*[164,165], described the need to standardize the indication and dosage of antiviral therapy in the management of HSK[164,165]. Ultimately, the decision to treat and treatment regimen selection is largely dependent on the individual clinician[166]. Lázaro-Rodríguez *et al*[167] reported isolated primary herpes-simplex virus neuroretinitis in an immunocompetent adult; thus, underpinning the need for starting antiviral therapy for individuals with macular stars who are not immunocompromised but seropositive for HSV IgM after ruling out other infectious causes, ionizing radiation, and arterial hypertension[167].

Antiviral resistance of HSK is generating concern, but the exact mechanisms of resistance have not been fully articulated[168]. Acyclovir is the most common drug used in the management of HSK[169], although eyedrops are now being proposed[170]. Resistance to acyclovir occurs due to extended use[171], and mutation in the viral thymidylate kinase and DNA polymerase which decreases enzyme affinity for its substrate[172-174]. Topical cyclosporine drops and prednisolone acetate drops are statistically similar in potency for stemming inflammation and preventing scar development[175].

HSK may predispose the eye to opportunistic infections. Vigilance must be applied when managing HSK patients with steroid-antibiotic eye drops as this is contraindicated[176]; and can result in epithelial defects and vascularization[177]. On the other hand, steroid-antiviral therapy performs better than fixed antiviral therapy[178].

In scenarios where the clinician is considering treatment-related side effects or conventional antiviral therapies not giving the required results, oral Valganciclovir could be used as an alternative for treatment and prophylaxis against HSK [179]. Watson *et al*[180] described a novel way of attacking the dormant LAT responsible for reactivating HSK after periods of latency using adeno-associated virus vectors to prevent reactivation[180]. A novel antiviral agent, SC93305, reportedly showed effectiveness against acyclovir-resistant strains of HSV-1 & HSV-2; SC93305 also reportedly did not interfere with host humoral immune responses[181]. Amentoflavone was found to inhibit resistant strains of HSV-1 including HSV-1/106, HSV-1/153, and HSV-1/blue by interfering with early-stage transcription of viral genes[182].

Novel delivery approaches such as prodrugs, nanocarriers, and peptides do cover against the systemic toxicity of oral antiviral prescription, as well as the rapid nasolacrimal clearance of topical antiviral therapy. The use of gel formulations and novel delivery approaches function tremendously to achieve desired outcomes[183].

The prophylactic use of antiviral agents such as acyclovir and valacyclovir is successful in treating HSK[184]. Cacicol® which is a topical eye biopolymer that contains poly-carboxymethyl glucose sulfate solution has been identified to have antiviral action on HSV and Varicella Zoster Virus (VZV)[185]. Due to emerging resistance to antiviral medication, there is a need to use other medications that target other viral proteins. This prompted Guan *et al*[186] to study the effect of stapled peptides on HSV-1 DNA synthesis and HSV-1 infection[186].

In the application of antiviral therapy for recalcitrant HSK, epithelial debridement, high-frequency dosing, and reduction of immunosuppression could help in achieving a better outcome[187].

IMMUNE RESPONSES IN HERPES SIMPLEX KERATITIS: IMPLICATIONS FOR DISEASE MANAGEMENT

The infection of the cornea by HSV secondary to an immune-inflammatory reaction by proinflammatory T cells is a significant cause of vision impairment[188].

There is a greater incidence of HSV infection in patients with atopy and the course of HSV keratitis in patients with severe atopic disease is usually more difficult to manage[189]. Patients with immune deficiencies or atopy usually present with bilateral HSK and it has been proven that long use of antiviral therapy can reduce the recurrence rate[190].

Presenting as an unwanted side effect, HSK has been found to spontaneously occur in those managed for MDA5-DM with rapidly progressive interstitial lung disease with tofacitinib at a dose of 20 mg per day[191].

Lappin *et al*[192] trialed immunotherapeutic management of HSV *via* topical administration of an ocular activating nanoparticle, feline models exhibiting re-occurrence of HSK were managed with this nanoparticle therapy and showed marked improvement as demonstrated by reduced viral shedding and ocular morbidity markers[192]. Davido *et al*[193] derived the KOS-NA mutant HSV mutant as a vaccine for the prevention of HSV-1[193,194]. Their data suggests that the mutated agent performed considerably well by preventing keratitis eruption in a mouse model.

Matundan *et al*[195], suggested that the ICP22 gene of HSV protected a murine model against corneal scarring[195]. Plasmid DNA administered with Interleukin 4, 10, 12, and 18 is reported to reduce inflammation and subsequent scarring in HSK[196]. Naidu *et al*[197] reported that the human HSV1 VC2 vaccine administered intramuscularly to mice mitigated the expression of HSK after subsequent infection with HSV-1 (McKrae) virus[197]. Similar results using the HSV1 VC2 vaccine in mice were shown to protect against HSV virus-linked immunopathogenesis[198].

Optineurin, a host protein, has been suggested as a possible inhibitor of the spread of HSV-1 while also mitigating neural damage[199]. This may be due to its selective autophagy regulatory properties. Hirose *et al*[200] investigated the role of TH17 responses in an HSV-1-infected murine model and concluded that interleukin-17 protects against ocular morbidity secondary to HSV-1[200].

Periocular corticosteroid injection resulted in hypopyon formation in a small sample of patients with HSV stromal keratitis and endotheliitis; the subsequent resolution was reportedly gained with topical antivirals, steroids, and systemic antivirals[201]. Upon infection with HSV-1, innate immune TLR-2 forms dimers with TLR-1, TLR-2, and TLR-6, cytokines, and IFN. TLR-2/2 Ligand activates the expression of specific antiviral genes[202]. Multiple microRNAs (miRNA) suspected to play significant roles concerning host immunity are upregulated in tear film samples of patients with HSV-induced epithelial keratitis[203]. Tenascin-C, an extracellular matrix glycoprotein increased in expression following injury, was discovered on the corneal epithelium of eyes with HSK keratitis[204].

Understanding the crucial role immune response plays in the development of herpes simplex stromal keratitis is necessary to control Stromal keratitis, especially macrophages, T cells, proinflammatory cells such as Th1 and Th17 CD4 T cells, and in some cases CD8 T cells in addition to memory CD19+ and CD27+ cells[205-209]. The transmission properties of HSV keratitis would be better managed if the role of the CD4+ TRM (Tissue Resident Memory T cells) and their induction by vaccines is well understood[210]. CXCR4-expressing cells may be key in the migration of neutrophils and the progression of lymphatics onto HSV-infected corneas[211]. During latent stages, viral proteins maintain low-level sporadic expression without full virion production, and ganglionic HSV-1 specific CD8+ T cell retention during latency serves protective functions[212]. Priming CD8+ T lymphocytes formed a basis for the hypothesis of future vaccination against HSV-1 reactivation[212]. Novel epitope peptide/CXCL-10 based prime/pull HSV vaccine elicited increased migration of HSV-specific CD8+ T-cell lymphocytes to the cornea and trigeminal ganglia of human leukocyte antigen (HLA) transgenic rabbits, thus protecting against ocular herpes virus infection[213].

Plasmacytoid dendritic cells are the main source of IFN- α within corneal stroma; higher density of plasmacytoid dendritic cells was associated with better *in-vivo* immunity against HSV-1 inoculation[214]. Higher peripheral blood levels of interleukin-1 β in patients with inactive/Latent HSK were correlated with increased levels of STAT1 and IRF3: Essential proteins for antiviral immune responses[215].

Interleukin-27 production by macrophages limited HSV-1 corneal shedding and consequent disease progression in mice[216]. Enhancement of P13K-Akt pathway signaling was hypothesized to cause increased susceptibility to HSV infection among test mice[217].

TRIM21 has been hypothesized to regulate type-1 IFNs' response to viral pathogens. The absence of TRIM21 proteins in knockout mice reportedly correlated with greater HSV-1 titers within the trigeminal ganglion during acute infection [218]. IFN α /beta could represent promising immune-mediated targets in HSV-1.

Antibody-dependent cellular cytotoxicity immune mechanisms provide protection from both cutaneous and ocular manifestations of HSV-1 and-2 infection[219]. Hence, novel vaccines eliciting the production of polyfunctional antibodies can offer protection to the immune-privileged eye[219].

The absence of Lymphotoxin- α was reported by Wang *et al*[220] to affect the expression of HSK in mice[220]. Dhanushkodi *et al*[221] also discovered IFN- γ -producing PLZF α ROR γ tlo as the most prevalent Invariant Natural Killer 1 cells in HSK-infected corneas[221]. At the level of the infected endothelial layer, IFN regulatory factor-7 has been shown to upregulate acquired immunity and mediate the major histocompatibility complex resulting from HSV infection[222].

RECURRENT HERPES SIMPLEX KERATITIS: CLINICAL FEATURES AND PREVENTION STRATEGIES

HSK is known to lie latent for extended periods before being reactivated by any number of factors[223]. These factors may be as simple as ultraviolet radiation[35,126,129] to major ocular surgeries.

Tear fluid exosomes may be a site of HSV-1 Latency; involved in the spread of HSV-1 infection to human corneal epithelial cells (HCECs). Corneal grafts can also be a source of HSK infection if not properly screened[224]. With a global shortage of available viable cornea graft tissue, Li *et al*[225] demonstrated that porcine corneal tissue is a good option for human corneal tissue[225]. Recurrent HSK has been implicated in Deep Anterior Lamellar Keratoplasty failure[226]. It is therefore important to differentiate between HSV-linked endotheliitis and actual graft rejection[227]. The use of tectonic grafts for non-healing keratitis was reported by Tourkmani *et al*[228], with around 50% postoperative recurrence of HSK lesions by Suzuki *et al*[229]. Being elderly, male, and having a large graft > 9 mm are all risk factors for developing epithelial defects after penetrating keratoplasty[230].

Researchers have reported cases of HSV relapse with ocular presentations after Botulinum Toxin injection[231-233]. Recurrence of HSK dendritic epithelial keratitis should be considered for following CXL in keratoconus patients with suspicious history[234,235]. It has been postulated that the ultraviolet radiation A light, damage to the epithelial/stroma trauma, or damage to the nerves of the cornea during the cornea cross-linking could result in recurrent HSV[236,237]. However, other authors have advocated for corneal cross-linking as a therapy for HSK[238].

Mohanty *et al*[239] recommended a two-week steroid regimen for the management of HSV-induced interstitial keratitis [239]. Topical steroids have been reported to reduce the risk of stromal progression of HSK by up to 60%[240]. Stromal keratitis commonly occurs following Varicella-Zoster viral infection in children[241]. Instituting steroids empirically in all clinically suspected HSK cases without prior culture may result in aggravation of microbial differentials and long-term topical agent reliance[242].

Research has shown that HSV keratitis could recur after ocular surgery such as strabismus[243], penetrating keratoplasty, cataract, corneal crosslinking, lamellar keratoplasty, photorefractive, and phototherapy[244-247]. Intraocular

surgery, it seems, is also a risk factor for HSV reactivation with uveitic presentation[248]. Latent HSV in morphologically normal donor corneal grafts reactivated following keratoplasty[249].

There is substantive evidence for the prophylactic use of oral medications in penetrating keratoplasty who have had a previous history of HSK[250]. Herpetic keratitis lesions were found in a section of keratoconus eyes after collagen cross-linking procedures[251]. Small incision lenticule extraction has also been reported to precede a case of HSK manifestations[252]. Laser-assisted in-situ keratomileusis and photorefractive keratectomy triggered HSV reactivation which presented as endotheliitis in some patients post-corneal refractive surgery[253]. In another case reported by Basak and Basak[254] and Samak, oral Valacyclovir was used to resolve acyclovir-resistant endotheliitis resulting from deep membrane epithelial keratoplasty[254].

Nutritional deficiencies with subsequent hematologic abnormalities may trigger a recurrence of HSK[255]. Long-term use of systemic immunosuppressants for treating autoimmune disorders like systemic lupus erythematosus (SLE), lymphoproliferative diseases; and prophylaxis of organ transplant rejection, increases the likelihood of HSV recurrence/reactivation[256-259]. In certain individuals, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) vaccination triggers a cascade of autoimmune responses that can reactivate herpetic keratitis[260,261]. There were some reported incidences of reactivated herpetic keratitis following the reception of SARS-CoV-2 vaccines; patients' immune status before vaccination was not specified[262-266]; one patient had prior PKP surgery owing to HSK scarring[263]. Palpebral demodex infestation was associated with refractory and recurrent herpetic keratitis[267].

A retrospective study reviewing a large sample size from Canadian health databases reported no causal recurrence of HSK due to topical antiglaucoma medications[268]. Ozturk *et al*[269] reported a case of HSK in an adult male patient one week after receiving Ranibizumab. Behera *et al*[270] reported another case of reactivation of HSK in eyes and they investigated after instilling bevacizumab[270]. A similar occurrence was also detailed by Al-Kaabi and Choremis[271]. Eyes with previous herpetic keratitis or uveitis were reported to manifest more recurrent episodes following phacoemulsification without longer periods of disease quiescence[272].

COMPLICATIONS OF HERPES SIMPLEX KERATITIS: CORNEAL SCARRING AND VISION LOSS

Kim *et al*[273] described the clinical features of HSK showing the most common subtype as epithelial keratitis (49.7%) followed by stromal keratitis (23.5%). They also show that epithelial keratitis had the highest likelihood of recurrence. The most common complication was cornea opacity. There was a 32.2% recurrence of HSK. The recurrence rate was seen to be less in the group that used prophylactic antiviral agents and the ascorbic acid treatment group[273]. There are bi-directional relationships between HSK and Atopic dermatitis[274].

Stromal involvement is usually a precursor for corneal scarring due to the infiltration of inflammation regulatory agents[275]. Rao *et al*[276] in their study showed the development of lacrimal gland inflammation in a mouse model of herpes stromal keratitis underpinning the inflammatory origin of herpes stromal keratitis[276]. Ocular infestation of the HSV is usually secondary to an infection in another part of the body[277]. Buccal to ocular transmission is a common transfer route. HSV keratitis can cause cornea scars which can make it difficult for intraoperative procedures such as cataract surgery and implantation of intraocular lenses[278]. That said, a follow-up of 37 HSV-infected eyes undergoing cataract surgery returned reasonably good outcomes even though the authors advised cataract surgeons to ensure the disease is latent before surgery. Scarring secondary to HSK is thought to result from the infiltration of inflammatory bodies and angiogenesis[279,280]. Corneal subbasal nerve density reduces markedly even after keratitis lesion scarring in eyes infected with HSV[281,282]. Subbasal nerve density losses, and consequent corneal hypoesthesia, are less in cases of herpetic epithelial keratitis[282]. Stromal inflammation in HSK is believed to be Chemokine (specifically ACKR2) mediated[283]. Hence these chemokines can determine the amount of ocular involvement in an individual.

Yoshida *et al*[284] reported on a case of HSV in a 64-year-old immunocompetent female who developed corneal scarring even after the resolution of HSK[284]. A similar presentation managed by Pisitpayat *et al*[285] did not progress to corneal scarring and had better outcomes[285]. HSV has also been associated with a risk of developing Neurotrophic Keratopathy[286-289]. In children and neonates who have suffered HSK episode(s), the possibility of amblyopia and strabismus in the latter years is present[290].

Herpetic keratitis is the leading cause of cornea ulcer and corneal perforation in the world, recurrence of the condition predisposes the individual to developing cornea ulcer and perforation. HSK has been found to cause neurotrophic keratitis[291-293]. HSK may also be a causative factor of corneal graft failure[294,295]. Using OCT, Ichikawa *et al*[296] were able to show an increase in cornea densitometry in HSV-affected eyes[296]. Retrograde inflammation from the cornea to the anterior chamber can result in viral anterior uveitis[297]. This is usually characterized by granulomatous precipitates with/without cornea scarring. HSV may also lead to uveitis. Posterior uveitis has been postulated to occur following long periods of post-keratitis latency[298].

Testing an HSK-compromised eye presents unique challenges for the patient and the clinician. Tananuvat *et al*[299] reported corneal perforation secondary to non-contact tonometry in two cases with thin corneas secondary to HSK and scarring[299]. Rebound tonometry may be more appropriate as it presents less stress to the corneal tissues.

HSK has been found to get worse in areas where air pollution is more frequent[300].

HSK has been associated with cornea denervation, although a certain degree of cornea nerve regeneration occurs a lot of the nerves do not come back to normal[301]. Sensory neuronal voltage-gated ion channels were associated with pain propagation in HSV-1 infection[302]. Further investigations are needed to probe a possible association between HSK and limbal stem cell deficiency as a sequel[303]. This may account for cases of poor corneal re-epithelialization[304]. Limbal stem cells' loss in herpetic keratitis was associated with density alterations of central basal epithelia, and the subbasal

nerve plexus[305]. Moein *et al*[306], using a specific HSV-1 strain KOS-63 showed that the recurrence of HSK causes more denervation[306].

Chirapapaisan *et al*[307], demonstrated the reduction in corneal subbasal nerve density (CSND) using *in vivo* confocal microscopy denoting the reduction in CSND even in contralateral eyes that did not show any scar[307]. The location of the cornea scar has a role to play in the lower likelihood of cornea regeneration[308].

It has been discovered that METTL3 (Methyltransferase 3) promotes pathological angiogenesis through canonical Wnt and VEGF signaling[309]. Ultraviolet A light used to carry out corneal collagen cross-linking could cause or trigger reactivation of latent HSV in a patient without clinical symptoms[310]. HSK has been reported to predispose individuals to be affected by *Burkholderia cepacia* which usually affects people with cystic fibrosis or immunocompromised[311]. Montgomery *et al*[312] postulated that ocular glands could be affected by HSV infection or other bacterial infections of the cornea[312]. The mentioned underlying physiopathological mechanisms in HSK can give rise to corneal scarring, vision loss, intraocular pressure elevation, and glaucoma.

NOVEL THERAPEUTIC APPROACHES FOR HERPES SIMPLEX KERATITIS: CURRENT RESEARCH TRENDS

Stopping the reactivation of HSK is essential for the development of vaccine strategies against HSV-1[313]. The discovery of a vaccine for HSK has been plagued with concerns about their overall safety for the public, leading to non-licensure and eventually shutdown of these labs[314]. Carr *et al*[315] demonstrated that higher doses of their HSV-1 0ANLS vaccine were able to prevent HSV-mediated disease[315].

It has been discovered that intrastromal injection of Bevacizumab could result in the regression of neovascularization in patients with neurotrophic keratitis secondary to HSV infection[316]. Topical therapeutic management is plagued with many factors including corneal epithelial toxicity to antiviral drops[317] and the development of tolerance[318]. The HEDS study recommended a guideline for oral antiviral drugs as a safer method of managing this disease process[319, 320]. Intravenous acyclovir was reportedly therapeutic for herpetic stromal keratitis[321].

The use of Retinoic acid to stabilize regulatory T-cells which mediate inflammation and control the progression of stromal keratitis in an HSK model[322]. Wang *et al*[323] engineered a mouse with knocked-out signal peptide peptidase and demonstrated that these mice expressed reduced viral replication and reactivation as compared to control mice[323, 324]. Sodium polyanethanol sulfonate has also been described to reduce the replication of HSV in corneal epithelial cells [325].

Antiviral therapy is the mainstay in the management of HSK, The development of vaccines against the HSK virus has met a roadblock due to therapeutic effects in humans which are controversial, even though several vaccine candidates are effective in animal models that would require testing in humans[326]. One such vaccine was developed and reported by Hasan *et al*[327] using selected proteins from ViralZone, however, it remains to be tested on animal models[327]. The use of certain chemical compounds that can modulate the chromatin state of the viral genome resulting in the enhancement of antiviral immunity or suppression of infection and recurrence is another option; novel therapeutic techniques such as CRISPR/Cas9 (Clustered Regularly Interspaced Short Palindromic Repeats) have significant potential to make changes in the latent viral DNA in sensory neurons and as such cure the neuronal location of the infection[328-333]. Wu *et al*[334] have also reported on AT-533, a heat shock protein-90 antagonist that expressed inhibitory effects on HSV keratitis.

The fermented extract of the Pomegranate fruit has been shown to alleviate inflammation and pain associated with HSK[335]. Similarly, Zannella *et al*[336] used a grape pomace extract to heal and prevent HSK lesions[336] successfully. Staying with herbal management options, Ribelato *et al*[337] reported that the *Trichilia catigua* extract shows promise as a therapeutic agent for the management of HSV/HSK[337]. Topical application of selected insulin formulations has also shown promise in accelerating re-epithelization in infective keratitis[338]. Extracts from the carnivorous purple pitcher plant have also been demonstrated to inhibit early viral transcription of HSV-1[339].

Maqsood *et al*[340] successfully used Omnilenz® to manage corneal epithelium defects successfully. They were able to adapt the contact lens to apply an amniotic membrane-derived cell matrix with 57% of recipients reporting complete resolution of lesions after treatment[340]. Varela-Garcia *et al*[341] also designed a special hydrogel contact lens to carry Acyclovir and Valacyclovir. They reported that the contact lenses so designed were able to carry Valacyclovir better than Acyclovir. They concluded that these special hydrogel contact lenses are a viable tool for extended delivery of antiviral therapy to infected eyes[341]. BostonSight developed the PROSE special contact lenses for clearing chronic corneal opacities. The Boston keratoprosthesis (KPro) is another example of an artificial cornea used in cases of HSK affecting corneal clarity[342]. Cressey *et al*[343] reported a case series where the PROSE was successfully used to clear corneal scarring in HSK patients[343]. In addition to contact lenses, ocular inserts are now being designed to provide continued delivery of the drug inside the eye[344]. Autologous bone marrow stem cells also show promise in managing immune-mediated corneal inflammation with little or no side effects[345,346].

Cryopreserved amniotic membrane has been used as adjuvant therapy[347]. Conversely, Insulin-Like Growth Factor Binding Protein-3 worsens HSK keratitis, hence its downregulation may mitigate HSK expression[348]. Treating human cornea explants that are infected with HSV with cold atmospheric plasma (CAP) has been shown to deactivate HSV-1 and lessen the severity[349]. Ointment-based matrix regenerating agent also offers some promise in the treatment of neurotrophic corneal ulcers secondary to HSK[350].

MiRNAs are novel discoveries that deepen our understanding of disease processes in the body[351]. Amniotic membrane transplantation is a good option for managing indolent epithelial keratitis and HSK in diabetic patients following cataract surgery[352]. Drops formulated from peripherally derived autologous blood may quicken the healing

of neurotrophic HSV keratitis[353]. miRNAs affect infection in the eyes by regulating the human immune system[354]. An attenuation of miR-155/miR-183/96/182 mitigated the intensity of PA keratitis in feline models as reported by Xu and Hazlett[355]. miRNAs have also been used to deliver HSV-1-erasing lentiviral particles, blocking the reoccurrence of HSV in at least three disease models[356].

The TBK1 and IKK ϵ inhibitor, bx795 has been reported to suppress HSV-1 both *in-vivo* and *in-vitro*[357]. In a study carried out by Zhang *et al*[358], they identified Ras-related C3 botulinum toxin as a potential target for treating HSV-1-related diseases using NSC23766 and Ehop016[358]. Following subconjunctival injection in mice, a novel SHIP-1 activator, AQX1125, reduced CD4+ lymphocyte infiltration *via* modulation of P13K signaling[359-360].

Diphenyleneiodonium (DPI), an inhibitor of NADPH Oxidase 2, yielded a reduction in ROS release from neutrophils; thus, DPI was hypothesized to ameliorate herpetic stromal keratitis *via* its reduction effects[361].

Harringtonine, isolated from *Cephalotaxus harringtonia*, showed potential as a novel viral entry inhibitor to strains (HSV-1 blue & HSV-1 153) with resistance to acyclovir by targeting herpesvirus entry mediator (HVEM)[362]. Fujimoto *et al*[363] suggested the use of HVEM and nectin-1 products as therapeutic and preventive drugs against HSV-1 and HSV-2 infection particularly nectin-1 Lg as an eyedrop[363].

Subconjunctival injection of PKHB1 peptide in murine eyes infected with HSV-1 triggered the release of antigen-presenting cells, CD8+ lymphocytes, and other immunodeficiency cascades which were attributed to the alleviation of viral antigens[364]. One percent dispirotriperazine gel proved efficacious for the resolution of HSV keratitis in preclinical rabbit models[365]. Small interfering (siRNA) delivered to HSV-infected *in-vitro* cells with an adenovirus type-5 vehicle showed potential for prophylaxis *via* inhibition of herpesvirus replication[366]. Inhibiting effects on 'disruptor of telomeric silencing 1-like' (Dot1 L) by siRNA and EPZ ameliorated corneal inflammation *via* non-release of ROS both *in-vivo* & *in-vitro*[367]. Dendritic cell-based DNA vaccination relieved manifestations of primary and recurrent HSK in murine experiments[368]. The rare sugar, i-picose was identified as a promising novel therapeutic target in murine HSV-1-related diseases, including HSK[369].

Pigment Epithelium Derived Factor has been shown in mice to reduce the severity of HSK[370]. An atypical presentation of presumed herpetic stromal keratitis was reportedly controlled following inoculation with *Staphylococcus aureus* lysates[371]. Ke *et al*[372] demonstrated the role of the FAK/PI3/Akt signaling pathway and MMP-2 and MMP-9 play in the development of HSK[372]. In treating stromal keratitis, it is important to add topical steroids to quell inflammation[373].

Topical Tacrolimus has been shown to improve visual acuity and reduce cornea inflammation, neovascularization, and cornea scarring, thus it is possible to inculcate it into the armamentarium of HSK management[374]. Transplantation of acellular porcine corneal stroma was a viable short-term substitute in a sample of Chinese patients with HSK keratitis[375].

Gene therapy (using an adenovirus type-2 vector) *via* meganuclease delivery to HSV-1 infected rabbit cornea transplantation models led to reduced HSV expression and attenuated immune responses[376]. Metabolic reprogramming *via* intraperitoneal metformin in mice infected with ocular HSV led to reduced expression of HSK lesions; with marked limitation of CNS complications induced by attempted metabolic therapy with 2-deoxy-d-glucose[377]. Lipid mediators are suggested to mediate the induction and mitigation of inflammatory processes. Zhang *et al*[378] have suggested that the Lipid mediator 11(12)-EET is potentially able to treat HSK[378].

The use of Von Willebrand factor has been identified as a good anchor to help in the delivery of therapeutics to prevent scarring and poor vision secondary to damaged cornea surface[379].

Dhanushkodi *et al*[380] discovered the use of engineered fibroblast growth factor-1 as a novel technique to reduce primary and recurrent HSK[380,381]. Shan *et al*[382] further suggested a crucial role oleanolic acid plays in the treatment of HSV keratitis, especially skin lesions HSV zosteriform model[382]. $\gamma\delta$ T cells in the cornea help in early immune defense against several infections including HSV, exploring further ways to boost its response to HSV could prove crucial in managing the condition[383].

Transcriptomic data and bioinformatic analysis could possibly provide clues into the detailed molecular mechanism of HSK action and the potential therapeutic targets[384]. Targeting the IL-27 which is a pro-inflammatory cytokine controlled CD4+ Foxp3+ Tregs (regulatory T-cells) could aid in treating HSV stromal keratitis[385,386].

Minegaki *et al*[387] in their study showed that tandem pentapeptides repeat a derivative of Major royal jelly proteins found in royal jelly has an anti-inflammatory ability which is beneficial in reducing IL-6 and TNF- α which are stimulated in HSV infection of the cornea[387].

In their work Rao and Suvas stated the role of hypoxia in the development of HSK lesions, they investigated the expression of hypoxia-associated glycolytic genes in HSV-1 infected corneas laying a great foundation for more research into inflammatory hypoxia and hypoxia associated genes and the possibility of targeting hypoxia-inducible factor[388]. Wang *et al*[389] suggested that blocking the interaction between glycoprotein K and signal peptide peptidase may have a therapeutic effect in the management of HSV-1-associated eye disease[389].

Jiang *et al*[390] in their research suggested that BMS-265246(CDK) which is a CDK $\frac{1}{2}$ inhibitor is effective and potent against HSV-1 especially as it interferes with multiple steps in the replication of HSV-1[390]. Sumbria *et al*[391] in their study suggested a dietary change to increase levels of short-chain fatty acid as a possible modality to be in place to reduce the impact of herpes recurrence in humans[391]. Majmudar *et al*[392] in their work showed strong evidence to support that SPGG (sulfated pentagalloylglucoside) is a viral entry inhibitor against HSV infection of the eyes[392].

CONTACT LENS-RELATED HERPES SIMPLEX KERATITIS: RISK FACTORS AND PREVENTION

Contact lenses have been implicated in infectious processes[393]. Subramaniam *et al*[394] detailed a case report of HSK in a contact lens wearer that completely resolved on oral antiviral therapy of 800 mg of Acyclovir five times daily alone [394]. However, it should be noted that Acanthamoeba is more likely to cause keratitis in contact lens wearers than HSV [395-397]. AK is occasionally misdiagnosed as HSV in, especially, very early stages[398,399]. Toshida and Sadamatsu also reported an incidence of HSK in a myopic individual wearing contact lenses for orthokeratology[400].

Live-attenuated vaccines may also show promise in preventing outbreaks of HSK. These vaccines introduce a weakened strain of the virus to the body, thereby allowing the body to develop natural defenses to the disease[401].

PEDIATRIC HERPES SIMPLEX KERATITIS: UNIQUE CONSIDERATIONS AND MANAGEMENT

In childhood stromal keratitis is the most common cornea manifestation of HSV infection; it usually progresses with scarring, residual astigmatism, and amblyopia. The recurrence rate is higher in the pediatric population especially those with immunosuppression[402]. Autosomal recessive Tyrosinemia type II presents with pseudo-dendritic keratitis and palmoplantar hyperkeratosis in affected infants and young children[403]. It is a worthy differential in the pediatric population.

Identifying HSK and treatment in children is challenging as they are at high risk for developing visual morbidity and a more aggressive HSK course that results in the scarring of the cornea and possibly amblyopia[404]. HSV keratitis should be considered as a differential diagnosis in a pediatric patient with keratitis[405].

In the management of HSK in children, the use of oral acyclovir as prophylaxis is safe, and its efficacy is related to compliance with therapy[406]. The incidence of HSK in penetrating patients who had cornea refractive surgeries is higher than in the general population[407].

Pediatric patients who have undergone penetrating keratoplasty for HSK have been shown to experience graft rejection, this must be diagnosed to minimize permanent damage significantly[408,409]. Treatment of pediatric HSK usually involves acyclovir, which generally gives a good prognosis[410]. Suppressive oral therapy may however be needed in the future if a recrudescence occurs after initial topical therapy. Of worthy mention is the ability of the pediatric myelogenous leukemia drug 6-thioguanine to mitigate HSV both *in vitro* and *in vivo*[411].

HERPES SIMPLEX KERATITIS IN IMMUNOCOMPROMISED PATIENTS: CHALLENGES AND TREATMENT OPTIONS

The SARS-CoV-2[412] has been implicated in HSV Keratitis[413,414]. HSK has been reported to relapse post mRNA coronavirus disease 2019 vaccination[415]. Herpetic eye disease has been seen to result more from individuals who received the BNT162b2 vaccine than those who received the mRNA-1273 or Ad26.COV2.S vaccines[416].

An atypical type of HSV keratitis, Archipelago Keratitis has been identified in immunosuppressed persons[417,418]. Table 1 below summarizes further literature on HSV occurrence in immunocompromised individuals[419-434].

SURGICAL INTERVENTIONS FOR HERPES SIMPLEX KERATITIS: CORNEAL TRANSPLANTATION AND BEYOND

Descemet membrane endothelial keratoplasty has been identified as an effective option for treating cornea edema resulting from HSV-1-related endotheliitis[435-438]. Novel endothelium-free grafts with endothelial cell regenerative capability may improve outcomes for high-risk transplant cases secondary to chronic HSV endotheliitis[439]. Intensive antiviral prophylaxis could reduce the risk of graft failure and recurrence of the condition[440]. The use of topical steroids, antibiotics, and higher doses of oral acyclovir leads to better postoperative outcomes of deep anterior lamellar and penetrating keratoplasties for corneal scarring caused by HSK[441].

There are several surgical interventions for the management of HSK but it basically involves either the replacement of the infected tissue or support of the tissue to aid healing. Cornea neurotization is gaining more acceptance today[442-444]. Lin and Lai reported a novel technique where the supratrochlear nerve of the same side as the affected eye was tunneled to the cornea to re-innervate damaged trigeminal nerve fibers with good results[445]. Bourcier *et al*[446] also reported similar results using the Lateral Antebrachial Cutaneous Nerve *via* a minimally invasive cornea neurotization procedure[446].

Roberts *et al*[447], reported the usefulness of sutureless tectonic pul-through mini-DSAEK in the management of corneal perforations secondary to herpes simplex infection or other causes[447]. New Onset HSK after keratoplasty could be managed by antiviral medications or amniotic membrane transplantation[448].

A Bowman's layer onlay graft is relatively easier as it does not resolve to deeper keratoplasty, it has the potential to reduce superficial cornea scarring and/or anterior cornea abnormalities[449]. Amniotic membrane transplantation reduces ocular opacity and scarring by inhibiting the secretion of inflammatory cytokines and fibroblast proliferation[450, 451].

Table 1 Selected literature on herpes simplex virus occurrence in immunocompromised individuals

Ref.	Predisposing condition	Summary
Gupta <i>et al</i> [419]	Necrotizing fascitis	HZO was the first sign of reactivation of varicella-zoster
Murgova and Balchev[420]	COVID-19	COVID-19 vaccines caused a reactivation in HSV ocular diseases
Yildiz <i>et al</i> [421]	COVID-19	COVID-19 vaccines caused a reactivation in HSV ocular diseases
Huang <i>et al</i> [422]	COVID-19	HSK was the 3 rd most common corneal complication after COVID-19 vaccination
Matharu <i>et al</i> [423]	Cancer	VZV and HSV cornea co-infection in a patient with systemic immunosuppression
Cohen <i>et al</i> [424]	COVID-19	Herpetic cornea infection may develop post SARS-CoV-2 vaccinations
Yoshida <i>et al</i> [425]	RA	Individuals with RA have the tendency to develop HSK which is usually more severe due to their immunocompromised state
Fei <i>et al</i> [426]	COVID-19	HSK could happen after vaccination with a possible preponderance
Al-Dwairi <i>et al</i> [427]	COVID-19	Reactivation of HSK on cornea graft after taking SARS-CoV-2 mRNA vaccine
Majtanova <i>et al</i> [428]	COVID-19	Five incidences of HSK after COVID-19 vaccination
Roberts <i>et al</i> [429]	COVID-19	Negative result of COVID-19 in the tears in a patient with recurring HSV Keratitis
Kuziez <i>et al</i> [430]	COVID-19	HSK was reviewed as an adverse effect occurring after COVID-19
Mohammadzadeh <i>et al</i> [431]	COVID-19	HSK-suspected reactivation resulted in corneal graft rejection
Ichhpujani <i>et al</i> [432]	COVID-19	HSK was implicated in a review of associated complications reported after vaccination
Ono <i>et al</i> [433]	Human herpes virus	Reactivation of HHV-6B infection
Sinha <i>et al</i> [434]	Psoriasis	HSV keratitis after taking secukinumab for the treatment of psoriasis

COVID-19: Coronavirus disease 2019; HSV: Herpes simplex virus; HSK: Herpes simplex keratitis; SARS-CoV-2: Severe acute respiratory syndrome coronavirus 2; RA: Rheumatoid arthritis; HZO: Herpes zoster ophthalmicus; VZV: Varicella zoster virus; HHV-6B: Human herpes virus 6B.

Lamas-Francis *et al*[452] reported the use of amniotic membrane transplantation for corneal ulceration secondary to infectious causes, they reported a success rate of 62.8% with 37.2% requiring additional surgery[452]. Similarly, Hayek *et al*[453] reported using a lyophilized amniotic membrane for the treatment of a 2 mm wide perforating cornea ulcer and didn't need keratoplasty[453].

Corneal trauma during surgery poses special problems due to the possibility of recrudescence of latent HSV infections in carriers. Preventive medication before surgery has been suggested for HSV seropositive patients[454]. Patients with comorbid ocular conditions such as cataracts could undergo Penetrating Keratoplasty before the cataract surgery as it has been shown in the literature that this has fewer complications and higher graft survival rate[455].

Graft failure after Penetrating Keratoplasty is common in eyes with HSK, hence it is important that HSV-1 or VZV PCR testing is done on all explanted cornea[456]. High-dose antivirals with prolonged tapering steroid doses prior to performing mushroom keratoplasty on eyes with herpetic vascularized corneal scars resulted in lower rates of graft failure and immunologic rejection in a longitudinal study conducted by Yu *et al*[457]. There were also higher than normal rates of graft failure with the Boston type I KPro for eyes having prior corneal HSV infection[458]. Suzuki *et al*[228] considered lamellar graft patching a safe and effective option for managing corneal perforations secondary to HSK-associated neurotrophic keratopathy[228].

Tape splint Tarsorrhaphy has been identified as a useful inexpensive technique to treat Persistent corneal epithelial defects[459]. Hata-Mizuno *et al*[460] reported a case of conjunctival epithelial ingrowth after PKP in a patient with Herpetic corneal keratitis[460].

CONCLUSION

The quest for better diagnosis, prevention, and management of HSK was uppermost in the minds of sampled participants in a paper by Liu *et al*[461]. Novel corneal active storage mediums enable better study and research of *ex-vivo* disease patterns in herpetic keratitis[462]. In the future, target extraocular (maxillary) vaccination to inhibit ocular herpes simplex reactivation may improve the epidemiology of the disease[463].

FOOTNOTES

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