Systemic Immunomodulatory Strategies in High-risk Corneal Transplantation

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INTRODUCTION

The first human corneal allograft was performed by Eduard Zirm in 1905; that is 49 years before the first successful solid organ (kidney) transplantation. The efficacy of this surgical procedure made it the most common form of human solid tissue transplantation with more than 100,000 procedures performed annually worldwide, and about 40,000 in the USA.[1] Due to corneal immune privilege, corneal transplantation has been associated with high success rates, including 90% survival after 1 year and 55% after 15 years when performed in avascular and non-inflamed host beds.[2-4]

The most frequent cause of corneal graft failure is rejection, which is an immune reaction against the donor cornea. Thirty percent of transplanted corneas experience at least one episode of immune reaction, and in low-risk cases one third of these, eventually lead to graft failure.[5-7] The reported incidence of corneal graft rejection varies from 2.3% to 68%,[8] and this depends on the presence of high-risk factors, most notably corneal neovascularization.[5,6]

Corneal transplantation in a non-vascularized and non-inflamed host bed, which is termed as low-risk (LR) corneal graft, does not require any systemic immunosuppressive agents. In this article, we will review the systemic immunosuppressive agents most commonly used for high-risk corneal transplantation, which include corticosteroids, cyclosporine A, tacrolimus, mycophenolate mofetil, and rapamycin. Benefits, risks, and published data on the use of these medications for high-risk corneal transplantation will be detailed. We will also summarize novel immunoregulatory approaches that may be used to prevent graft rejection in high-risk corneal transplantation.

Keywords: Corneal Transplantation; Graft Rejection; High-risk Graft; Immunomodulation; Immunosuppression

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Systemic Immunomodulatory Strategies in High-risk Corneal Transplantation

Tulio B. Abud, MD; Antonio Di Zazzo, MD; Ahmad Kheirkhah, MD; Reza Dana, MD, MPH, MS

Massachusetts Eye and Ear Infirmary, Department of Ophthalmology, Harvard Medical School, Boston, Massachusetts, USA

Abstract

The cornea is the most commonly transplanted tissue in the body. Although corneal grafts generally have high success rates, transplantation onto inflamed and vascularized host beds, or so-called high-risk corneal transplantation, has a high rate of graft rejection. The management of this high-risk corneal transplantation is challenging and involves numerous measures. One of the key measures to prevent graft rejection in these cases is the use of systemic immunosuppressive agents. In this article, we will review the systemic immunosuppressive agents most commonly used for high-risk corneal transplantation, which include corticosteroids, cyclosporine A, tacrolimus, mycophenolate mofetil, and rapamycin. Benefits, risks, and published data on the use of these medications for high-risk corneal transplantation will be detailed. We will also summarize novel immunoregulatory approaches that may be used to prevent graft rejection in high-risk corneal transplantation.

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placed in inflamed and vascularized host beds, so-called high-risk (HR) corneal transplantation, in which the graft has a 5-year survival rate below 35% with immunosuppression. These outcomes are considerably worse than those following first grafts of the kidneys, heart, or liver.

In this review, first we will provide an overview on risk factors for corneal transplant rejection and prophylactic measures to prevent transplant rejection in HR settings. Then, in more detail, we will review the systemic immunosuppressive therapies that are currently available to prevent rejection in HR corneal transplantation.

**HIGH-RISK CORNEAL TRANSPLANTATION**

In HR corneal transplantation, allograft rejection represents the main cause of corneal graft failure, with rejection rates of 50-70%, even with maximal immunosuppression. Multiple risk factors have been identified to increase the rate of immune reaction [Table 1]. Re-grafting of a failed transplant or performing a transplant in the context of pre-existing conditions, such as ocular surface inflammatory or infective disease, makes the eye more susceptible to an alloimmune reaction. Moreover, a clinical history of glaucoma and previous surgeries, particularly glaucoma surgery, raises the risk of graft rejection. This risk also increases by performing an eccentric transplantation or using a larger donor graft, which increases the exposure of alloantigens to the immune system. Finally, the risk of rejection is higher in very young recipients, during pregnancy, or after blood transfusion.

Host bed vascularity is, however, by far the most common risk factor for corneal allograft rejection. The normal cornea is devoid of lymph and blood vessels, and actively maintains its avascularity in a condition known as corneal angiogenic privilege. In a LR environment, the vascular sprouting subsequent to surgery is quickly inhibited, and the angiogenic privilege is restored. In HR recipients, loss of angiogenic privilege leads to blood and lymphatic vessel invasion into the corneal graft. These corneal neovessels are critical in delivering immune effector cells to the graft site. In addition, clinically invisible lymphatics play a critical role in trafficking alloantigens to host T cells in lymphoid tissue, which in turn initiate immune reaction and promote graft rejection.

The extent of corneal neovascularization correlates with the risk of allograft rejection, and several studies have implicated that the involvement of deeper corneal layers by neovascularization is important in inciting an immune alloantigenic response. It is well known that the number of corneal quadrants invaded by vessels as well as the number of vessels in each quadrant increase the risk of rejection. Khodadoust et al defined the rejection risks based on the degree of host bed vascularization: avascular, mild (1-3 vessels), moderate (4-10 vessels) and heavy (>10 vessels). They noted that, in heavily vascularized eyes, 65% of grafts started to reject, and all grafts finally failed despite strong immunosuppressive treatment.

**Management of High-risk Corneal Transplantation**

Management of corneal transplantation varies depending on the patient’s degree of risk. Postoperative prophylactic immunosuppressive regimens can be devised according to the level of risk.

In LR recipients, topical corticosteroids are the routine regimen during postoperative management and also for the treatment of endothelial graft rejections which occurs uncommonly in these cases. In the past, this treatment has proven effective in improving survival rates of LR corneal transplantation patients. However, the duration of prophylactic treatment with topical corticosteroids is still variable among surgeons.

New surgical techniques to improve graft outcomes have been focused on lamellar keratoplasty to prevent the risk of rejection by reducing the amount of allogeneic tissue transplanted and also avoiding endothelial cells which are the target for alloimmune responses. In addition, technical advances, such as globe fixation and Flieringa ring, graft suturing techniques, donor storage media and other technical factors (e.g., avoiding larger and eccentric grafts, and using nylon sutures instead of silk) have been reported to decrease graft failure rates due to non-immune factors. However, survival of corneal grafts at high risk for rejection has improved little over the past decades, even with new surgical devices and techniques, and new therapeutic strategies.

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**Table 1. Risk factors for corneal graft rejection**

| Preoperative | Intraoperative |
|--------------|---------------|
| Corneal neovascularization (number of quadrants, depth of vessel invasion) | Donor (larger size, eccentric graft) |
| Regrafting (2 or more) | Young recipient |
| Glaucoma | HLA mismatching (controversial) |
| Previous surgery | |
| Pre-existing ocular surface inflammation or infection | |
| Concomitant chronic inflammatory diseases | |
| Pregnancy | |
| Blood Transfusion | |

HLA, human leukocyte antigen
Interestingly, responders to the periodical survey of the Cornea Society felt that graft rejection occurs much less frequently after endothelial keratoplasty as compared to penetrating keratoplasty, considering the lack of difference in rejection prophylaxis or treatment strategies between the two procedures.[20] In addition, recent studies have significantly shown lower rates of corneal graft rejection following endothelial keratoplasty rather than penetrating keratoplasty.[23,26] For example, Anshu and colleagues reported rejection rates of 18%, 12%, and <1% after penetrating keratoplasty, Descemet stripping endothelial keratoplasty (DSEK), and Descemet membrane endothelial keratoplasty (DMEK), respectively.[27] However, it should be noted that in HR settings, the survival of endothelial keratoplasty is also very low.[28,29] Moreover, in HR settings, many corneas may have neovascularization and scarring which make them unsuitable for endothelial keratoplasty alone.

The human leukocyte antigen (HLA)-matching strategy in HR corneal transplantation is used only in some European centers; better survival rates have been shown mostly with minor ABO-antigen matching.[30,31]

The surgical timing of corneal transplantation, moreover, can have some effect on the survival of HR transplants. In mice, regression of lymphatic vessels occurs 6 months after any inflammatory process, and surgery at this time point results in a better outcome.[32] Thus, if possible, keratoplasty should be performed in an inflammation-free stage of the disease. However, further studies are needed to investigate these insights within the context of human corneal transplantation.

A novel treatment strategy for HR corneal transplantation is inhibiting corneal angiogenesis via blocking the vascular endothelial growth factor (VEGF).[33] Topical treatment with specific antibodies, trap proteins, or receptor antagonists has been shown to successfully prevent rejection in complicated grafts.[33,34] In addition, gene therapy has been used to maintain an immunosuppressive environment in the host bed,[35,36] and to inhibit the direct pathway of the antigen-presentation process by depleting antigen-presenting cells (APCs) in the donor cornea.[34]

Although the above-mentioned measures can be used to reduce the risk of rejection in HR corneal transplants, the key step in the management of these patients is the use of immunosuppressive therapy to dampen the immunologic pathways leading to rejection. The importance of postoperative immunosuppressive regimens for reducing the incidence of graft failure is supported by findings of the Collaborative Corneal Transplantation Study (CCTS),[37] which showed an improved graft survival with a strict topical corticosteroid regimen. However, doubts have been raised as to whether all patients in the CCTS were truly at high risk, because the authors attributed the improved graft survival found in their HR cases to the use of intensive topical steroid therapy postoperatively, close personal follow-up, and excellent patient compliance and understanding. On the other hand, the Castroviejo Cornea Society survey reported that 85% of patients at high risk of allograft rejection received therapeutic agents other than topical corticosteroids.[38]

In HR corneal transplantation, the use of corticosteroids is the first choice for prophylactic treatment. Prednisolone 1% or dexamethasone 0.1% drops represent the treatment of choice among Cornea Society members, and in the survey of United Kingdom cornea surgeons, the Bowman Club, these corticosteroids were administered between 6 to 8 times per day, including at night time. The duration of this regimen varies widely among the surgeons, with an average of 8 months among respondents in the Cornea Society survey.[20] The duration is also dependent on whether the host is phakic or pseudophakic. In the latter case, corticosteroids can be continued longer. However, because of the reduced efficacy in HR settings, several studies are currently investigating the effect of subconjunctival or systemic steroid treatment to achieve a better outcome.

### SYSTEMIC THERAPY

The aims of managing HR corneal transplants are, first, to inhibit or cause regression of corneal lymph- and hemangiogenesis[16,39-41] and subsequently, to prevent or reverse immune-mediated graft rejection. Systemic immunosuppressive agents are administered on a prophylactic basis in patients with a very high risk for rejection, especially those with salvageable vision in only one eye. However, a defined treatment strategy for different degrees of high risk status is not available, thus indications for this systemic treatment are often based on the surgeon’s judgment. This implies wide variability in treatment and also makes it more difficult to compare different studies.

While systemic corticosteroids and immunosuppressive agents may be partially effective in preventing graft rejection, their use is limited due to a wide range of ocular side effects, including infection, cataract formation and glaucoma, as well as potential systemic life-threatening systemic side effects, which may outweigh any improvement in corneal graft survival.[42-45]

In contrast to the outcomes reported for grafts of vascularized organs, the long-term survival of corneal grafts, in general, has not improved over recent decades, probably because the modern immunosuppression regimens that have exerted such a beneficial influence on other organ graft survival rates are generally neither effective nor appropriate for corneal transplantation.[46]

A number of shortcomings are evident in published reports on systemic immunosuppression in corneal transplant recipients:[47] (1) lack of risk factor stratification in some patients with failed grafts; (2) variable duration
of prophylaxis, conflicting outcomes even in studies using similar regimens; and (4) comparison of patients with HLA-matched and non-matched donor corneas.

Comparison of results between studies is also difficult because of the use of oral steroids in the first weeks after transplantation in some studies.

Below, we summarize systemic immunosuppressive medications widely used to prevent graft rejection in HR corneal grafts.

**Corticosteroids**

Corticosteroids represent the key medication for management of corneal transplantation. They can be used pre-, intra-, or postoperatively. Systemic corticosteroids have been used, either as monotherapy or in combination with other immunosuppressive agents to prevent corneal graft rejection in HR settings as well as to treat acute rejection. The report by the Cornea Society Survey showed that oral prednisolone (40 to 80 mg/day for 2 to 7 days) is prescribed by 22% of the surgeons, almost always as an adjunct to topical treatment, and sometimes as prophylactic treatment for corneal graft rejection. The usual dose is 60-80 mg daily (depending on body weight); however, the duration of treatment is widely variable, ranging from 1 day to 12 months. Currently, there is no consensus on the best time to start and end immunosuppressive treatment in patients who have undergone a corneal transplantation.

Kim et al, in an animal model of corneal transplantation, proposed that the preoperative use of corticosteroids, two weeks before grafting, could be sufficient to prevent or decrease angiogenesis before the insult of surgery and, therefore, improve outcomes. In fact, some studies have revealed that pretreatment with corticosteroids decreases host bed neovascularization in both LR and HR corneal transplantations.

Systemic administration of other steroids, such as a single-dose of intravenous have been considered by 14% of surgeons in HR situations such as in vascularized corneas and in cases with previous rejection. A single intravenous dose of 125 mg methylprednisolone sodium has been advocated for management of severe graft rejection in association with hourly topical corticosteroid drops. Alternatively, it has been shown that a single 500 mg intravenous pulse of methylprednisolone in severe endothelial rejection appears to be at least as effective as oral administration, while avoiding potential side effects of prolonged oral medication. In a study by Hill et al, the pulse therapy group achieved a 79% graft survival rate as compared with 63% for the oral group. Among recovered grafts, only 25% of those in the pulse group developed an additional episode of rejection, while 67% of eyes in the oral group did. This suggests that pulse therapy may confer some degree of long-term protection. However, another study focusing on administering a second pulse given either 24 or 48 hours after the first pulse did not report any significant improvement.

**Cyclosporine A**

Cyclosporine A (CsA) is a macrolide with powerful immunosuppressive activity that modulates T cell function. It is an 11-amino acid peptide isolated from the fungus *Tolypocladium inflatum*. Cyclosporine A acts by binding to the intracellular protein cyclophilin, which inhibits the activity of calcineurin enzyme, blocking nuclear factor activation. Cyclosporine A inhibits the interleukin (IL)-2 pathway, leading to a decrease in the synthesis and secretion of several pro-inflammatory cytokines such as IL-2, IL-4, interferon-γ (IFN-γ), tumor necrosis factor-α (TNF-α), and thus results in inhibition of helper and cytotoxic T cell differentiation. Cyclosporine A also improves allergic reactions by inhibiting mast cells, and plays a role in cell apoptosis in autoimmune diseases.

Because of its mechanism of action, CsA has been extensively used to prevent immune rejection after solid-organ transplantation. However, it can cause strong adverse events, such as hypertension, nephrotoxicity, hepatotoxicity and gastrointestinal toxicity, when high doses are taken orally or intravenously for a long time.

In ophthalmology, CsA has been used both topically and orally for a multitude of indications. To avoid the systemic side effects and deliver greater amounts of the medication into the eye, topical CsA has been prescribed for years and has gained popularity among ophthalmologists to treat different immune disorders, including dry eye disease, vernal keratoconjunctivitis, and ocular graft-versus-host disease. Oral CsA has also been used to treat a variety of diseases including...
uveitis, Vogt-Koyanagi-Harada disease, and Graves’ orbitopathy.[75,76]

For corneal transplantation, both systemic and topical CsA have been used to prevent graft rejection. Previous studies on oral CsA are summarized below. The use of oral CsA for prevention of immune rejection in HR corneal transplantation has been studied and described in the literature for decades, but to date a consensus has not been reached about the real effectiveness of this medication. Several authors have published results showing that systemic CsA administration can improve the outcome of HR corneal transplantation. Table 2 summarizes the related articles. In a prospective study, Hill and colleagues reported that CsA-treated corneal graft recipients had a significantly higher rejection free rate as compared to the untreated control group (73% and 49% respectively, \(P < 0.001\)).[43] These authors also described that graft rejection is decreased when CsA is taken for 12 months instead of a shorter period of 4 to 6 months.[77] Other retrospective studies have further suggested the benefit of oral CsA regarding survival and rejection rates [Table 1].[78-80]

In contrast, several studies have reported either no or only limited effectiveness of oral CsA administration in HR corneal transplantation.[43,44,81,82] A retrospective study observed only a limited effect of CsA in preventing immune reactions and reported no significant difference between the control and treatment groups in terms of rejection or failure rates.[44] Poon et al as well as Inoue et al, in retrospective case-control reports, also failed to find a significant difference in rejection and failure rates between the CsA-treated group and the control group.[43,81] In a recent prospective, randomized trial, Shimazaki et al observed no statistically significant effect from the systemic use of CsA regarding the rates of rejection (30% and 16%, respectively) and failure (45% and 42%, respectively), although all rejection episodes in the treatment group occurred after the drug was discontinued.[82] In agreement with Reinhard et al,[80] the authors hypothesized that oral CsA may be effective while in use and could shift the immune response from acute to chronic. This would “postpone” a rejection episode to a chronic clinical course, which could be diagnosed and treated more efficiently.[80,82] In a different prospective randomized trial, Reinhard et al compared oral CsA to oral mycophenolate mofetil (MMF), and found no statistical difference between the groups in graft rejection and failure.[83]

The questionable effects of oral CsA in preventing corneal graft rejection may be due to the fact that, although it achieves a high concentration in the serum, it does not reach the aqueous humor and thus may not be able to prevent the loss of ocular immune privilege following HR corneal transplantation.[82,84] In addition, the severity of primary host disease, duration of treatment, and occurrence of side effects can all cloud the real effect of the drug.

Variable results on the effectiveness of CsA for preventing corneal graft rejection may also be partly explained by different dosage and blood levels of CsA in different studies. In most studies, blood levels of 75 to 400 ng/mL had been maintained during the treatment period.[43,44,78,81] However, a recent study used blood concentrations after 2 hours as the method to monitor

### Table 2. Previous studies on systemic cyclosporine administration for high-risk corneal transplantation

| Reference          | Study Design | No. of patients | Duration (months) | Rejection (%) | P     | Failure (%) | P          | Overall systemic adverse events (%) | Blood level of CsA (ng/mL) |
|--------------------|--------------|-----------------|-------------------|---------------|-------|-------------|-----------|------------------------------------|--------------------------|
| Miller et al,[79]  | RS           | 15              | 3                 | 27            | NP    | NP          | 27        | NP                                 | 27                       | 200-400                  |
| 1998               |              |                 |                   |               |       |             |           |                                    |                          |
| Hill et al,[81]    | PS           | 43              | 4-12              | 49            | 73    | <0.001      | NA        | 76                                 | 21                       | 130-170                  |
| 1994               |              |                 |                   |               |       |             |           |                                    |                          |
| Reinhard,[80]      | RS           | 131             | 9.4               | NP            | NP    | NP          | 31.3      | NP                                 | NP                       | 100-150                  |
| 1996               |              |                 |                   |               |       |             |           |                                    |                          |
| Poon et al,[43]    | CCS          | 49              | 12                | 37            | 53    | 0.16        | 29        | 37                                 | 45                       | 75-180                   |
| 2001               |              |                 |                   |               |       |             |           |                                    |                          |
| Inoue et al,[81]   | CCS          | 27              | 5.4               | 30            | NP    | 0.81        | 38*       | NP                                 | <0.05**                  | 100-150                  |
| 2001               |              |                 |                   |               |       |             |           |                                    |                          |
| Reinhard et al,[83]| PRS          | 27              | 69.4              | 19            | 28    | NS          | 31        | 27                                 | 0.33                     | 120-150                  |
| 2001               |              |                 |                   |               |       |             |           |                                    |                          |
| Rumelt et al,[44]  | RS           | 28              | 12                | 32            | 42    | NS          | 68        | 92                                 | 18                       | 200-400                  |
| 2002               |              |                 |                   |               |       |             |           |                                    |                          |
| Shimazaki et al,[82]| PRS          | 20              | 6                 | 30            | 16    | 0.24        | 45        | 42                                 | 1.0                      | 600-1000                 |

RS, retrospective study; PS, prospective study; CCS, case-control study; PRS, prospective randomized study; NP, not presented; NS, not significant; *After 2 years of follow-up; **Graft failure incidence was higher in CsA group

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the concentration of the drug, and kept it between 600 and 1000 ng/mL.\textsuperscript{[83]} The latter approach has been used after renal transplantation, and may be more accurate in controlling drug concentration for transplantation follow-up.\textsuperscript{[83]} Due to its variable absorption, monitoring of CsA blood levels as well as liver and renal function tests are mandatory.\textsuperscript{[86]} Poon et al reported a 45% incidence of adverse events during oral administration of cyclosporine, with kidney dysfunction as the most common side effect.\textsuperscript{[83]} While other studies did not report such a high percentage of side effects, they did describe systemic adverse events including nausea, hypertension and elevated blood levels of creatinine and urea.\textsuperscript{[44,77,78,81,82]}

### Tacrolimus

Tacrolimus, or FK506, is a macrolide antibiotic with potent immunosuppressive activity, which is isolated from the soil fungus \textit{Streptomyces Tsukubaensis}. This calcineurin inhibitor has a mode of action similar to that of CsA. Its mechanism of action initiates with binding to a class of peptidyl-prolyl cis-trans isomerasers, known as FK506-binding proteins (FKBPs), especially FKBP-12\textsuperscript{[87,88]}. Subsequently, a complex of tacrolimus-FKBP-12, calcineurin, calcium and calmodulin is created, leading to inhibition of calcineurin's ability to dephosphorylate the nuclear factor of activated T cells. Thus, the initial phase of T cell activation is blocked, resulting in inhibition of T-lymphocyte signal transduction and IL-2 transcription. Additionally, release of TNF-\(\alpha\), IFN-\(\gamma\) and other cytokines is also affected by tacrolimus.\textsuperscript{[89,90]} Tacrolimus has been reported to entail fewer systemic side effects than CsA, even given that its immunosuppressive effect is 25-100 times more powerful than CsA.\textsuperscript{[91,92]} Clinical trials have shown that its efficacy is greater than CsA for liver, kidney and pulmonary transplantations, and the medication is also less prone to induce systemic hypertension and lipid abnormalities.\textsuperscript{[83-86]}

In ophthalmology, tacrolimus has been effectively used to treat immune-mediated ocular disorders such as atopic keratoconjunctivitis,\textsuperscript{[86]} posterior uveitis,\textsuperscript{[87]} and chronic graft-versus-host disease.\textsuperscript{[89,90]} Furthermore, because of its potent immunosuppressive effects, tacrolimus has been used in various studies to prevent graft rejection in HR hosts as detailed below.

Systemic tacrolimus (2-12 mg daily) has been shown to reduce graft rejection in HR corneal transplantation, with a graft survival of 65%.\textsuperscript{[100]} The therapeutic target range of 1 to 12 mg/L was achieved with a mean daily dose of 4.4 mg. However, the optimum length of treatment is still not known.\textsuperscript{[101]} Hypertension (23%) is the most common side effect of tacrolimus treatment, followed by headaches, malaise and gastrointestinal upset.\textsuperscript{[100]}

In a prospective study, Yamazoe et al showed that treatment with tacrolimus (10-20 ng/mL) resulted in significantly fewer graft rejection episodes and longer graft survival than CsA, probably due to its more effective suppression of alloimmunity.\textsuperscript{[102]} Moreover, patients treated with tacrolimus tolerated the drug better than those treated with CsA; however, 20% discontinued tacrolimus treatment because of renal dysfunction and muscle pain, which might also be related to previous CsA treatment they had received. Furthermore, 30% of the grafts failed without rejection, possibly because of previous history of glaucoma.

In another study, Joseph et al found that only 8 of the 43 corneal transplant patients who used tacrolimus prophylactically (1 mg twice daily) had rejection episodes, and 5 of these experienced rejection related graft failure.\textsuperscript{[100]} These patients might have benefited from higher doses of tacrolimus or a combination treatment with another immunosuppressive agent.

In an animal model of corneal transplantation, a combination of FK506 and MMF delayed graft rejection for 3 weeks. The Gray’s survival model, stratified according to the type of recipient (low risk and high risk), showed that tacrolimus monotherapy more effectively reduced the risk of rejection than did MMF monotherapy.\textsuperscript{[103]}

### Mycophenolate Mofetil

Mycophenolate mofetil (MMF) is another type of immunosuppressant used systemically after organ transplantation.\textsuperscript{[104]} It is the pro-drug of the active substance mycophenolic acid (MPA), a potent inhibitor of inosine monophosphate dehydrogenase, which inhibits the de novo synthesis of guanosine nucleotides, resulting in selective inhibition of T- and B-lymphocyte proliferation.\textsuperscript{[105,106]} As T and B cells are predominantly dependent on de novo synthesis of guanosine nucleosides, the purine biosynthesis of these cells is relatively selectively inhibited. Other cells are either not, or less, affected by MMF as the result of their ability to use alternative salvage pathways of purine synthesis.\textsuperscript{[105,107]}

Mycophenolate mofetil has been demonstrated to be effective and safe in kidney and heart transplantations at a dose of 3 g per day and for liver transplantation using a dose of 2 g per day.\textsuperscript{[108-111]} The most common reported side effects are infections, anemia, leukopenia, and gastrointestinal disturbances; however, blood monitoring is generally unnecessary and reserved for special situations, such as severe adverse events or treatment failure.\textsuperscript{[111]}

In ophthalmology, MMF has been used to treat uveitis and HR corneal transplantation.\textsuperscript{[62,76,83]} In a preliminary report of a prospective, randomized, multicenter trial with 86 patients, Reinhard et al described an immune reaction free rate of 89% in the MMF-treated group in contrast to 67% in the control group (\(P = 0.03\)) during the first year after surgery.\textsuperscript{[112]} In this study, both groups
received early postoperative systemic corticosteroids and topical corticosteroids for 5 months. Patients classified as high-risk, in the MMF-treated group, received 2 g of MMF per day for 6 months in addition to the corticosteroid treatment. After a mean follow-up period of 3 years in the same cohort, Birnbaum et al reported a reaction-free graft survival rate of 83% in the MMF-treated group and 64.5% in the control group (P = 0.04).\textsuperscript{[113]} Regarding graft failure, no statistically significant difference was found between the two groups, although the percentage of graft failures as a result of rejection was noticeably higher in the control group (20% vs. 78%). Mycophenolate moftil was relatively well tolerated, as many of the reported side effects were not likely due to MMF administration, and only 2 patients out of 57 in the MMF group had to stop taking the medication because of the side effects. The main adverse events were gastrointestinal disturbances, arterial hypertension and hyperlipidemia. Similarly, to test MMF as an agent for prophylaxis in HR keratoplasty, Mayer et al conducted a trial in which 10 patients with prior herpetic disease underwent penetrating keratoplasty and received MMF 2 g per day for 1 year. According to the authors, there were two instances of mild rejection with no influence on endothelial cell density and no recurrence of herpetic disease.\textsuperscript{[114]}

There are only a few published articles comparing the safety and efficacy of CsA and MMF. In a prospective randomized trial including 41 patients, Reis et al showed no significant difference between CsA and MMF in terms of rejection episodes (10% vs. 9.5%, respectively), graft survival (100% in both groups), and occurrence of adverse events in a HR setting during a follow-up of about 10 months.\textsuperscript{[115]} The authors suggested that MMF or CsA in combination with a short postoperative course of oral corticosteroids are similarly effective in preventing acute rejection following HR corneal transplantation. Moreover, they concluded that the broad and safe therapeutic range (2 or 3 g/day) of MMF avoids major side effects and also frequent checkups; therefore, MMF is more likely to be administered in patients with suboptimal compliance who fail to visit the ophthalmologist or general practitioner on a regular basis. Reinhard et al published the results of the same trial with a follow-up of about 3 years, and still reported no significant difference between CsA and MMF treatment groups in graft survival (74% vs. 69%, respectively) and rejection-free rate (73% vs. 53%, respectively, P = 0.46), even though the CsA group had a lower rejection percentage.\textsuperscript{[89]}

In a retrospective study with 417 HR keratoplasties, Birnbaum et al reported a significantly greater effect from MMF in preventing graft rejections as compared to CsA after 3 years of follow-up (72% vs. 60%, respectively, P = 0.03), but with no significant difference in terms of graft survival (87% vs. 77%, respectively).\textsuperscript{[62]} However, this result may be in part due to patient selection, as according to the authors, the CsA group had more severely HR patients than did the MMF group. On the other hand, hosts that received combined CsA and MMF did not show a significant difference in immune reaction rates as compared with the other two. In fact, they found a lower rate of survival with combined treatment (67%, P < 0.01) when compared to the other two groups; this finding could be explained by patient selection bias with initially worse prognosis. In terms of safety, MMF-treated patients presented a lower percentage of side effects than did CsA-treated patients.\textsuperscript{[112]}

Another retrospective study had a large MMF group of 79 patients and a small CsA group of 5 patients, and demonstrated that the combination of the immunosuppressive agents with systemic acyclovir in patients with previous herpetic keratitis achieved a graft survival rate of 86.9% and rejection-free rate of 72.9%. Comparison between the groups could not be made due to the small sample size in the CsA group.\textsuperscript{[114]} It is known that MMF has a synergistic effect with acyclovir, thus this combination might be beneficial for patients undergoing keratoplasty after herpetic corneal disease.\textsuperscript{[114,117]}

In 2004, among the members of the Cornea Society that responded to a survey, only 14% and 0% of them were using systemic CsA or MMF, respectively, for prevention of HR corneal transplantation.\textsuperscript{[114]} These percentages may be higher currently due to the number of published studies about this matter. Several clinicians agree that MMF seems to have the same capacity as CsA in reducing the severity of shifting the immune reactions from severe to mild.\textsuperscript{[83,115]} In addition, MMF’s broad therapeutic range, a smaller percentage of severe side effects, and lower cost due to less blood monitoring, makes the drug more convenient for ophthalmic patients.\textsuperscript{[63,115]}

Rapamycin (Sirolimus, Rapamune)

Rapamycin is a bacterial macrolide isolated from \textit{Streptomyces hygroscopicus}, which has antifungal and immunosuppressive properties.\textsuperscript{[118]} Rapamycin forms a complex with the immunophilin FK binding-protein (FKBP-12), and the rapamycin-FKBP-complex inhibits the mammalian target of rapamycin (mTOR).\textsuperscript{[119]} Despite having a structure similar to that of tacrolimus, rapamycin is not a calcineurin inhibitor and thus not nephrotoxic. It acts by decreasing IL-2-mediated activation of T-lymphocytes with a blood concentration range of 12-20 ng/mL.\textsuperscript{[118,120]} Rapamycin has been shown to inhibit the growth factor induced proliferation of fibroblasts, endothelial cells and smooth muscle cells, which are also beneficial in solid organ transplantation.\textsuperscript{[121,122]}

In a prospective pilot study, Birnbaum et al showed a comparable efficacy regarding immune reaction-free corneal graft survival with the use of rapamycin and MMF. Specifically, no immune reaction was observed in either group at 6 months, while only two reversible
immune reactions occurred in the rapamycin group within 2 years of follow-up.[125]

Chatel et al also performed a prospective study on 6 patients with HR corneal transplantation. After 1 year of combination therapy with MMF and rapamycin, and then two years of rapamycin monotherapy, they showed 3 rejections episodes with 1 year of follow-up in 6 patients, of whom 1 had an irreversible rejection.[124] In addition, all patients developed hypercholesterolemia within 6 months of therapy. Therefore, the authors concluded that the combination of rapamycin and MMF was effective in extending corneal transplant survival, but generally the treatment was not well tolerated. Finally, the broad spectrum of side effects following treatment with rapamycin observed in these studies as well as in other solid organ transplantation studies, especially arterial thrombosis, appears to limit its safe usage.[125,126]

Novel Strategies for Immunomodulation

Several immunoregulatory approaches have been studied in animal models in recent years and have shown interesting results in increasing the survival of corneal grafts.

Suppression of antigen-presenting cell (APC) maturation by malononitrilamide (FK778) has been demonstrated to prolong corneal allograft survival in a rat keratoplasty model.[127] In addition, antibody based therapeutic agents have been developed to modulate the rejection of vascularized organ allografts. Specific systemic treatment with intact antibody can certainly prevent or delay corneal graft rejection in experimental animals.[128,129] A wide variety of polyclonal, monoclonal and recombinant antibodies have been tested targeting immune cell determinant or co-stimulatory molecules, such as IL-1 blockade,[130] leukocyte function antigen-1 (LFA-1), very late antigen-1 and 4 (VLA-1, VLA-4),[131,132] CD40–CD154 pathway,[133,134] CD28 and CD3 (CD80 and CD86).[135] It has been reported that Cytotoxic T Lymphocyte Antigen 4 protein (CTLA4-Ig), a fusion protein acting on B7-CD28 binding, can prolong corneal allograft survival after systemic injections in animal models by directly inhibiting T cell activation.[136] However, the efficacy of antibody therapy in humans is often limited by systemic side effects and the development of anti-idiotypic and anti-isotypic antibodies in the recipient.[137] In addition, the blood eye and ocular surface barriers limit access of whole antibodies into the eye. In fact, few of these studies in experimental animals[99,131,132–134] have been subsequently translated into clinical trials.[144,145]

It is worthy of note that there have been novel approaches to immunomodulate the alloimmunity focusing on morpholone oligonucleotides,[146] cell-specific gene therapy,[147] RNA interference,[148] tolerogenic APC,[149] and IL-2 therapy[150] with promising experimental results.

CONCLUSION

The cornea is the most commonly transplanted tissue. A significant number of grafts are performed in the inflamed and vascularized environment of high-risk hosts, which puts the patients at high risk of allograft rejection. The management of HR corneal transplantation is very challenging because of the low efficacy of long-term immunosuppressive therapy and their side effects. Many studies have recently been performed to find an immunosuppressive monotherapy or a combined therapeutic regimen that shows long-term efficacy with no major side effects. However, customized immunomodulation treatment appears to be the best management option for these difficult cases, for example, improved efficacy of CsA in patients with atopic keratoconjunctivitis, or of MMF in subjects with history of ocular HSV infections. Moreover, the use of MMF is suggested in patients with compliance issues or with systemic comorbidities.

In addition to application of novel immunosuppressive drugs and targeted biologic treatments that block specific pathways implicated in transplant immunity, there are a number of tolerance-inducing protocols including expansion of regulatory T cells (Treg) through interleukin-2 therapy or use of tolerogenic APCs that may hold promise in promoting corneal graft survival without the toxic side effects of systemic immunosuppressive medications.

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Conflicts of Interest

There are no conflicts of interest.

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