Interleukin 1 Receptor Antagonist Suppresses Allosensitization in Corneal Transplantation

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Objective: To delineate the mechanisms by which topical interleukin 1 receptor antagonist (IL-1RA) treatment promotes orthotopic corneal allograft survival.

Methods: Corneal buttons were prepared from eyes of C57BL/6 mice and placed orthotopically in normal or neovascularized (high-risk) eyes of BALB/c mouse recipients. Topical IL-1RA (or vehicle alone) was applied to grafts 3 times daily until the grafted eyes were enucleated. Corneal specimens were evaluated for content of Langerhans cells. A week after enucleation, 1 group of recipients was tested for allospecific delayed-type hypersensitivity elicited by intrapinnae injections of donor splenocytes. In companion experiments, a second group of mice that underwent transplantation, IL-1RA treatment, and enucleation was challenged with orthotopic skin grafts from B10.D2 donor mice (sharing minor H antigens with C57BL/6 mice) to determine whether the second group of mice could reject grafts bearing corneal donor minor H alloantigens in an accelerated fashion.

Results: Mice whose orthotopic corneal allografts were treated topically with IL-1RA acquired neither donor-specific delayed-type hypersensitivity (P<.001) nor the capacity to reject orthotopic donor-type skin allografts in an accelerated manner (P<.05), whereas controls treated with vehicle alone developed delayed-type hypersensitivity and rejected B10.D2 grafts in an accelerated manner. Moreover, IL-1RA–treated grafts placed in both high-risk (P = .01) and normal-risk (P = .004) eyes displayed significantly reduced levels of infiltrating Langerhans cells compared with vehicle-treated controls.

Conclusions: Topical IL-1RA promotes corneal allograft survival in large part by preventing activity of recipient Langerhans cells, and thereby preventing these cells from inducing systemic allosensitization. These data suggest that IL-1 plays a key role in promoting allosensitization when corneal allografts are placed orthotopically.

Clinical Relevance: Suppression of allosensitization by topical IL-1RA may prove a clinically useful method for enhancing corneal transplant survival.


CORNEAL transplantation is the most successful type of solid tissue transplantation in humans. However, immune rejection remains a significant clinical problem, and many patients lose sight from corneal graft failure. The extraordinary ability of allografts of cornea to survive when placed orthotopically has been ascribed to “immune privilege.” In general, major histocompatibility complex (MHC)–encoded class I and class II molecules expressed on cells within solid tissue grafts play a central role as targets of recipient T-cell–mediated alloimmunity, and bone marrow–derived antigen-presenting cells (APCs) located within grafts play a central role in the induction of alloimmunity. Both of these features are unusual in the normal cornea. The MHC class I and class II molecules are poorly expressed on cells of the normal cornea, especially the endothelial cells. Moreover, APCs, such as Langerhans cells (LCs), are essentially absent from the cornea, except at the limbus, hence, donor buttons are devoid of these cells.

Recently, we have shown that topical treatment of murine corneal allografts with interleukin 1 receptor antagonist (IL-1RA) suppresses transplant rejection, whether the recipient corneal beds were normal (ie, avascular) or high risk (ie, neovascularized). Long-standing corneal...
MATERIALS AND METHODS

MICE

Male mice aged 8 to 10 weeks were purchased from Taconic Farm (Taconic, NY). Animals with dystrophic or degenerative corneal calcific deposits were excluded from study. All animals were treated according to the Association for Research in Vision and Ophthalmology Statement for the Use of Animals in Ophthalmic and Vision Research. In corneal transplant experiments, BALB/c (H-2b) strain mice were used as recipients and C57BL/6 (major and minor allos disparate, H-2d) or BALB/c (syngeneic) strain mice were used as donors. In skin graft experiments, B10.D2 (minor disparate with BALB/c, H-2d) tail skin grafts were used.

INDUCTION AND GRADING OF CORNEAL NEOVASCULARIZATION

Corneal neovascularization (high-risk graft beds) was induced by intrastromal sutures as described previously.13 Briefly, 3 interrupted 11-0 nylon sutures were placed in the central cornea of 1 eye of a normal BALB/c mouse 2 weeks before transplantation on day -14 using aseptic microsurgical technique performed with an operating microscope. The neovascularized beds then received orthotopic corneal transplants on day 0 as described above (neovascularization-inducing sutures were removed at the time of transplantation).

RESULTS

EFFECT OF TOPICAL IL-1RA ON ACQUISITION OF DONOR-SPECIFIC DTH

To determine whether topical IL-1RA interfered with the induction of donor-specific DTH by orthotopic allogeneic cornea grafts, we needed first to describe the time at which systemic donor-specific DTH arises after corneal allografts are placed in high-risk and normal graft beds. Donor-specific DTH was assessed in transplant recipients 1 week after enucleation (weeks 1 and 2 after grafting and weeks 2 and 3 after grafting in high-risk and normal-risk recipients, respectively) and in positive control mice 1 week after subcutaneous immunization. As the results presented in Figure 1 (top) reveal, donor-specific DTH was detectable in mice exposed to donor corneas grafted to normal avascular eye beds at 3, but not at 2, weeks. Recipients of donor corneas in high-risk eyes (Figure 1, bottom) displayed donor-specific DTH when tested at both 1 and 2 weeks after grafting. Thus, corneal allografts in high-risk eyes induce systemic sensitization 1 to 2 weeks earlier than they do when placed in normal-risk avascular beds.

We next examined the effect of topical IL-1RA on the rapidity of acquisition of donor-specific DTH following orthotopic corneal allografts. Donor C57BL/6 corneas in place in normal-risk BALB/c recipients for 3 weeks, and in high-risk eye recipients for 2 weeks, before enucleation of the grafted eyes. Enucleation was necessary to prevent continuing exposure of the recipient immune system to donor antigens. While the grafts were in place, eyes received treatment with topical IL-1RA or vehicle only as described previously. The results are presented in Figure 2 (top, normal-risk eyes; bottom, high-risk eyes). Unlike positive controls, mice treated topically with IL-1RA displayed weak DTH responses that were indistinguishable from negative controls. We conclude that topical treatment with IL-1RA inhibits both normal- and high-risk orthotopic corneal allografts from inducing donor-specific DTH.

ORTHOTOPIC CORNEAL TRANSPLANTATION

As described previously,12 each recipient was deeply anesthetized with an intraperitoneal injection of 3 mg of ketamine hydrochloride and 0.0075 mg of xylazine hydrochloride before all surgical procedures. The central 2 mm of the donor cornea was excised and secured in recipient graft beds with 8 interrupted 11-0 nylon sutures (Sharpoint; Vanguard, Houston, Tex). Antibiotic ointment was applied to the corneal surface, and the eyelids were closed for 24 hours with a tarsorrhaphy using 8-0 nylon sutures. All grafted eyes were examined after 72 hours; no grafts were excluded from analysis because of technical difficulties. Transplant sutures were removed in all mice on day 7.

PHARMACOLOGICAL STRATEGY

In most experiments (unless noted in the “Results” section), topical preparations were applied in a masked fashion to the surface of eyes of BALB/c recipient mice on the day of grafting and 3 times daily thereafter until enucleation. The study medication was composed of human recombinant IL-1RA, 20 mg/mL, in 0.2% sodium hyaluronate in phosphate-buffered saline (supplied by Amgen, Boulder, Colo). Vehicle-treated animals received 0.2% sodium hyaluronate only.12

ASSSESSMENT OF DONOR-SPECIFIC DELAYED-TYPE HYPERSENSITIVITY

At appropriate times after grafting, 1 × 106 irradiated (2000 rad) spleen cells (in 10 µL of Hanks balanced salt solution) from donors syngeneic with the corneal graft were
injected into the right pinnae, as described previously. Posi-
tive controls were immunized by subcutaneous injection of 10×10⁶ spleen cells of the appropriate allogeneic strain 1 week before ear challenge. At 24 and 48 hours after ear challenge, ear thickness was measured in a masked fash-
ion with a low-pressure micrometer (Mitutoyo, MTI Corp, Paramus, NJ). Ear swelling was expressed as follows: spe-
cific ear swelling = (measurement of right ear at 24 hours – measurement of left ear at 24 hours – measurement of right ear at baseline) – (measurement of left ear at 24 hours – measurement of left ear at baseline) in microns. Ear swelling responses at 24 hours after injection are presented as a group mean ± SE measure-
ment. Since results at 24 and 48 hours were similar in all experiments, only 24-hour data are presented. All panels contained a minimum of 5 animals.

SKIN GRAFTS AND ASSESSMENT OF SKIN GRAFT SURVIVALBALB/c mice received an orthotopic skin graft from B10.D2 mice as described previously. Briefly, tail skin grafts (2×4 mm) were placed on graft beds prepared on the thoracic wall of anesthetized mice (halothane and atropine, Vedco, Arcadia, Calif). Petrolatum gauze was placed over the graft site. Antibacterial powder (nitrofurazone) was then applied, and the wound was covered with dry gauze fol-
lowed by a plaster cast wrapped around the thorax. One week later, the cast was removed, and the grafts were ex-
amined every day. Graft rejection was determined when the surface was judged by clinical inspection to be completely denuded of epidermis. In general, normal mice rejected their test skin allografts within 15 to 18 days.

EFFECT OF TOPICAL IL-1RA ON MIGRATION OF RECIPIENT LCs INTO ORTHOTOPIC CORNEAL ALLOGRAFTSC57BL/6 corneas were grafted into normal- or high-risk eyes of BALB/c mice that were subsequently treated with topical IL-1RA or vehicle. The results are presented in Figure 3. In normal graft beds treated with IL-1RA, the epithelium contained significantly decreased levels of LCs, compared with vehicle-treated controls at 2 and 3 weeks after grafting. Similarly, in high-risk graft beds, treatment with IL-1RA reduced the density of LCs within graft epithelium at 1 week (P = .07, borderline significance) and at 2 weeks (P < .01). Thus, topical IL-1RA suppresses migration of recipient LCs into corneal allo-
grafts.

EFFECT OF TOPICAL IL-1RA ON ACQUISITION OF ABILITY TO REJECT ORTHOTOPIC SKIN GRAFTSMice with alloimmunity reject orthotopic skin allo-
grafts in an accelerated fashion compared with nonim-
mune controls. Our objective in this series of experi-
ments was to test whether mice treated topically with IL-1RA could reject orthotopic skin grafts, syngeneic at minor alloantigen epitopes with the corneal grafts, in an accelerated fashion. High-risk corneal graft beds of BALB/c mice received C57BL/6 corneal grafts. The eyes were treated topically with IL-1RA or vehicle only as de-
scribed above. High-risk eyes of positive control mice were treated with vehicle alone. After 1 week, treatment was stopped and the graft-containing eyes were enucleated to prevent ongoing exposure of the recipient immune sys-
tem to donor-derived antigens. One week later, each re-
cipient received an orthotopic B10.D2 skin graft, and the survival of these grafts was assessed by visual inspec-
tion of the epidermis. The results are summarized in Figure 4. The median survival time of B10.D2 skin on BALB/c mice whose grafted eyes were treated with topical IL-1RA was 17 days, whereas the median survival time of skin grafts on BALB/c mice whose grafted eyes were treated topically with vehicle was 14 days. The rate of rejection of orthotopic B10.D2 skin grafts on mice that had received a C57BL/6 cornea treated only with ve-

LC ENUMERATION

Langerhans cell densities within corneal epithelium were as-

Langerhans cell densities within corneal epithelium were as-

ltered by an immunofluorescence assay as previously de-
scribed. Briefly, each eye was enucleated and the anterior segment dissected under the operating microscope. Topically treated eyes bearing corneal transplants were enucleated at either 2 to 3 weeks postoperatively (normal graft beds) or 1 to 2 weeks postoperatively (high-risk graft beds). The cornea was placed in 20 mmol/L EDTA buffer and incubated for 30 minutes at 37°C after which the epithelium was removed in toto and washed in phosphate-buffered saline at room tem-

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ARCH OPHTHALMOL/VOL 116, OCT 1998

mented was to test whether mice treated topically with

P values less than .05 were deemed significant.

statistical analyses were performed using the Student t test for comparison of delayed-type hypersensitivity (DTH) re-

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POTENTIAL SYSTEMIC EFFECTS OF IL-1RA APPLIED TO THE OCULAR SURFACE

It is possible that topically applied IL-1RA could interfere with immune induction systemically, as well as locally. To evaluate this possibility, syngeneic corneas were grafted onto high-risk beds of BALB/c mice, and the ocular surface was treated with topical IL-1RA or vehicle. Grafted eyes were enucleated 1 week later, and, after an additional week, B10.D2 skin was grafted to the thoracic wall of the BALB/c mice. To assess the impact on acquisition of systemic donor-specific DTH, a subgroup of the BALB/c animals received $10^6$ spleen cells (from C57BL/6 donors) 7 days after receiving syngeneic corneal grafts that were treated with either IL-1RA or vehicle for 10 days. Seven days thereafter, donor-specific DTH was assessed as described above. As the results displayed in Figure 6 indicate, mice treated with topical IL-1RA rejected B10.D2 grafts at the same tempo as vehicle-treated controls, and both groups rejected the grafts more slowly than did mice sensitized subcutaneously with C57BL/6 spleen cells. Moreover, mice treated topically with IL-1RA and then immunized subcutaneously with C57BL/6 spleen cells mounted donor-specific DTH responses comparable in intensity to those of mice treated with vehicle alone before subcutaneous immunization (Figure 7). Together, these results demonstrate that topical IL-1RA fails to alter alloimmunization initiated via nonocular routes. Hence, topical IL-1RA interferes with alloimmunization in the context of corneal transplantation via a local, rather than a systemic, mechanism.

![Figure 1](image1.png)
![Figure 2](image2.png)

**Figure 1.** Donor-specific delayed-type hypersensitivity in BALB/c recipients of C57BL/6 corneal transplants placed in normal-risk (top) or high-risk (bottom) eyes. Grafted eyes were retained for 1 to 3 weeks, then enucleated as indicated in the "Materials and Methods" section. Primed mice were immunized subcutaneously with C57BL/6 splenocytes. One week later, recipient ear pinnae were challenged with donor splenocytes. Mean (± SEM) ear swelling responses at 24 hours are presented. Symbols indicate responses significantly greater than those in naive controls: asterisk, P < .02; dagger, P < .003.

**Figure 2.** Donor-specific delayed-type hypersensitivity in BALB/c mouse recipients of C57BL/6 corneal transplants placed in normal-risk (top) or high-risk (bottom) eyes that were treated topically with interleukin 1 receptor antagonist (IL-1RA) or vehicle alone. Grafted eyes were enucleated at 3 weeks (normal-risk eyes) or 2 weeks (high-risk eyes). Primed mice were immunized subcutaneously with C57BL/6 splenocytes. One week later, the recipients were ear challenged and swelling responses assessed. Bar indicates SEM. Asterisks indicate responses significantly greater than those in naive controls (P < .005).
Along with IL-6 and tumor necrosis factor α, IL-1 is regarded as a prototypical inflammatory cytokine, and as such plays an important role in a wide array of immunoinflammatory states, ranging from endotoxin-induced septic shock to immune-mediated graft rejection. In the context of ocular immunity, IL-1 appears to play a critical role in initiating immune responses by virtue of its action on APC function. It has been shown in mice that suppression of IL-1 receptor function with IL-1RA can suppress corneal LC activity and restore immune privilege in eyes subsequent to an inflammatory insult. Moreover, topical IL-1RA can significantly reduce the rate of corneal allograft rejection in normal- and high-risk eyes. Our present results indicate that IL-1 plays a critical role in the induction of alloimmunity by orthotopic corneal transplants. To summarize that evidence, corneal allografts induced vigorous donor-specific alloimmunity, expressed, on the one hand, as accelerated rejection of orthotopic skin grafts syngeneic with the corneal graft donor and, on the other hand, as donor-specific DTH. Topical application of IL-1RA to eyes bearing a corneal allograft prevented recipient mice from acquiring donor-specific DTH and from rejecting donor-type skin allografts in an accelerated fashion. Together, these findings implicate IL-1 in the process by which an orthotopic corneal allograft alerts the recipient immune system to the graft.

Normally, the central cornea displays little evidence of IL-1–dependent activity. While IL-1 levels are very low in normal corneal tissue, its levels can be significantly up-regulated in inflammation. Along with the report of Niederkorn et al that LCs can be induced to migrate from the limbus into the central cornea by injection of IL-1 into the corneal stroma, our results suggest that IL-1 is an important potential chemoattractant for LCs within the cornea and that endogenous IL-1RA is the natural inhibitor that keeps LCs at the limbus. In the present experiments, topical IL-1RA prevented LCs from migrating into corneal allografts and simulta-
The graft bed is a high-risk eye, and there is a positive corneas grafted into high-risk eyes. The rapidity with which corneas containing LCs are promptly rejected at heteroclass II alloantigens. By contrast, class II MHC-disparate corneas without LCs are not rejected and are incapable of immunizing recipients to MHC class II MHC-disparate corneas without LCs are not rejected and are incapable of immunizing recipients to MHC class II alloantigens to recipient T cells. In this context, the normal cornea possesses few bone marrow–derived cells that could function as APCs, and, therefore, lacks passenger cells. This is relevant to recently published evidence that alloantigens expressed on corneal grafts are detected by recipient T cells almost exclusively by the indirect pathway of allorecognition. This pathway requires that recipient APCs infiltrate the graft and acquire, process, and present graft-derived alloantigens to recipient T cells. In this context, we propose that, in orthotopic corneal allografts, endogenous IL-1 entices APCs to migrate into the graft and thereby activate the “indirect” pathway of allorecognition. The value of IL-1RA as an immunosuppressant in this context rests on its ability to thwart the indirect pathway of allorecognition for a tissue that constitutively lacks the ability to activate T cells via the direct pathway.

Other reported approaches to suppression of alloimmune responses have relied on systemic administration of monoclonal antibodies, such as anti–leukocyte function–associated antigen 1 and anti-CD4. To our knowledge, our experiments with IL-1RA are the first example of a topical treatment modality that can promote corneal transplant survival by interfering with the induction of allosensitization. Moreover, this molecular strategy relies on a naturally produced cytokine that largely circumvents the concern of inducing immunogenic responses when foreign (nonself) proteins are used in immune modulation. It is hoped that the development of topical molecular therapies will make it possible in ophthalmology to suppress ocular inflammatory disorders and corneal graft rejection without incurring the undue risks that accompany systemic immunosuppressive therapies.

Accepted for publication May 14, 1998.

This work was supported in part by grants EY00363 (Dr Dana) and EY19765 and AR44130 (Dr Streilein) from the National Eye Institute, National Institutes of Health, Bethesda, Md, and by the Massachusetts Lions Eye Research Fund 8095-0703 (Dr Dana).
A look at the past...

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