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<td>Published Version</td>
<td>doi:10.1001/archophthalmol.2007.61</td>
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<td>Accessed</td>
<td>December 5, 2017 6:26:46 PM EST</td>
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Topical Omega-3 and Omega-6 Fatty Acids for Treatment of Dry Eye

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Objective: To study the efficacy of topical application of alpha-linolenic acid (ALA) and linoleic acid (LA) for dry eye treatment.

Methods: Formulations containing ALA, LA, combined ALA and LA, or vehicle alone, were applied to dry eyes induced in mice. Corneal fluorescein staining and the number and maturation of corneal CD11b+ cells were determined by a masked observer in the different treatment groups. Real-time polymerase chain reaction was used to quantify expression of inflammatory cytokines in the cornea and conjunctiva.

Results: Dry eye induction significantly increased corneal fluorescein staining; CD11b+ cell number and major histocompatibility complex Class II expression; corneal IL-1α and tumor necrosis factor α (TNF-α) expression; and conjunctival IL-1α, TNF-α, interferon γ, IL-2, IL-6, and IL-10 expression. Treatment with ALA significantly decreased corneal fluorescein staining compared with both vehicle and untreated controls. Additionally, ALA treatment was associated with a significant decrease in CD11b+ cell number, expression of corneal IL-1α and TNF-α, and conjunctival TNF-α.

Conclusions: Topical ALA treatment led to a significant decrease in dry eye signs and inflammatory changes at both cellular and molecular levels.

Clinical Relevance: Topical application of ALA omega-3 fatty acid may be a novel therapy to treat the clinical signs and inflammatory changes accompanying dry eye syndrome.

Arch Ophthalmol. 2008;126(2):219-225

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Dry Eye Syndrome (DES) is a highly prevalent health problem that affects more than 10 million people, primarily women, in the United States alone. It is a frequent cause of office visits due to ocular discomfort and commonly leads to problems with sustained visual activities such as reading and driving. Inflammation has been recognized as an important component of DES. The recently introduced topical cyclosporin A (Restasis; Allergan, Irvine, California) has been shown to decrease ocular surface inflammation, stimulate tear production, and improve signs and symptoms of dry eye, further signifying the role of inflammation and anti-inflammatory agents for dry eye treatment.

Naturally occurring essential polyunsaturated fatty acids (PUFA) of omega-3 (n-3) and omega-6 (n-6) series are promising natural anti-inflammatory agents shown to have beneficial effects in many inflammatory conditions such as rheumatoid arthritis and ulcerative colitis. The n-3 FAs include alpha-linolenic acid (18:3n-3; ALA) and its elongation and desaturation products, stearidonic acid (18:4n-3), eicosapentaenoic acid (20:5n-3; EPA), and docosahexaenoic acid (22:6n-3; DHA). The n-6 FAs include linoleic acid (18:2n-6; LA) and its products, gammalinolenic acid (18:3n-6; GLA), dihomogammainolenic acid (20:3n-6; DGLA), and arachidonic acid (20:4n-6; AA). Both ALA and LA are called “essential” FAs because they cannot be synthesized by mammals and must be supplied in diet.

Recent studies have shown beneficial effects of dietary supplementation of FAs in DES. In a cross-sectional study of 32,470 women, women with a higher n-3 FA intake (more than 5-6 tuna servings per week as opposed to less than 1) were found to have 68% lower prevalence of DES. In 2 randomized clinical trials, oral supplementation with LA and GLA ameliorated the signs and symptoms of dry eye. It is postulated that when the n-6 to n-3 ratio is approximately 4:1 or lower, the conversion of DGLA to AA undergoes competitive inhi-
bition with enhanced metabolism of DGLA to prostaglandin E1 (PGE1) series, an eicosanoid with anti-inflammatory properties. In aggregate, these data indicate that n-3 and n-6 FAs may play a role in the pathogenesis and treatment of DES. However, several important issues remain unresolved, in particular whether FAs can be provided topically, thereby bypassing excess caloric intake and gastrointestinal adverse effects associated with their oral supplementation. The purpose of this study was to evaluate the efficacy of topical n-3 and n-6 FAs using the controlled environmental chamber murine model of dry eye.

METHODS

INDUCTION OF DRY EYE

All animals were treated according to the Association for Research in Vision and Ophthalmology Statement for the Use of Animals in Research. The protocol was approved by the Schepens Eye Research Institute Animal Care and Use Committee. The details of the controlled environmental chamber and dry eye end points have been published previously. Dry eye was induced in 6- to 10-week-old C57BL/6 mice (Taconic Farms, Germantown, New York) for variable periods ranging from 2 to 10 days. Mice were placed in the controlled environmental chamber (relative humidity 30%, air-flow 15 L/min, temperature 21–23°C), modified with subcutaneous scopolamine administration for maximal ocular dryness. Scopolamine (Sigma-Aldrich, St Louis, Missouri) was injected in dorsal skin of mice (0.5 mg per 0.2 mL at 9 AM, 12 PM, and 3 PM; 0.75 mg per 0.3 mL at 6 PM). Controls were age-matched mice (relative humidity >80%, no air-flow, temperature 21–23°C, no scopolamine).

TOPICAL FA FORMULATIONS AND TREATMENT REGIMEN

Formulations tested included 0.2% ALA, 0.2% LA, and 0.1% ALA to 0.1% LA (1:1 ratio of n-3/n-6, total FA amount equal to the individual FA formulations). The FAs are water insoluble and hence require emulsification with compatible surfactants. The vehicle used consisted of the surfactants and emulsifiers Tween-80 (2.6%) and Glucam E-20 (2.6%), vitamin E as an antioxidant, mixed with a packing solution (water, boric acid, sodium borate, sodium chloride, and ethylenediaminetetraacetic acid) and prepared in an emulsion (Johnson and Johnson Vision Care, Inc, Jacksonville, Florida). Forty-eight hours after dry eye induction, each eye was randomized to receive one of the formulations or the vehicle. One microliter eye drop was applied topically to the eye of anesthetized mouse once daily from 48 hours to day 4 (total 3 doses) or day 9 (total 8 doses) depending on the time point studied. The untreated group received no eye drops. Signs of dry eye were measured 24 hours after the last dose (day 5 or day 10). Mice were then killed for cellular and molecular studies.

MEASUREMENT OF CORNEAL FLUORESCIN STAINING

Corneal fluorescein staining was performed at baseline (day 0), 48 hours (before administration of the first eye drop dose), day 5, and day 10. One microliter of 5% fluorescein was applied into the inferior conjunctival sac as previously described. Eyes were flushed with phosphate-buffered saline (PBS) to remove excess fluorescein at 3 minutes and examined with slitlamp biomicroscope in cobalt blue light. Punctate staining was recorded in a masked fashion using a standardized National Eye Institute grading system of 0 to 3 for each of the 5 areas of the cornea.13 Kruskal-Wallis and Mann-Whitney tests (unpaired data set) and Wilcoxon test (paired data set) were used for statistical analysis.

IMMUNOHISTOCHEMICAL STAINING

The following primary antibodies (BD Pharmingen, San Diego, California) were used for immunohistochemical staining: FITC-conjugated goat anti-Armenian hamster (code No. 127165-160) and Cy3-conjugated goat anti-Armenian hamster (code No. 016-160-084). For whole-mount immunofluorescence corneal staining, freshly excised corneas were washed in PBS and acetone fixed for 15 minutes. Nonspecific staining was blocked with anti-FcR CD16/CD32 antibody (BD Pharmingen, catalog No. 553142), and Streptavidin and Biotin blocking solutions (Vector Laboratories, Burlingame, California). The secondary antibodies (Jackson Laboratories, Bar Harbor, Maine) included Cy3-conjugated goat anti-Armenian hamster and (code No. 016-160-084) for whole-mount immunofluorescence corneal staining, freshly excised corneas were washed in PBS and acetone fixed for 15 minutes. Nonspecific staining was blocked with anti-FcR CD16/CD32 antibody (BD Pharmingen, catalog No. 553142), and Streptavidin and Biotin blocking solutions (Vector Laboratories, Burlingame, California). Next, the specimens were immunostained with primary or isotype antibodies for 2 hours, washed with PBS, incubated with secondary antibodies, and mounted using Vector Shield mounting medium (Vector Laboratories). Whole-mount corneal images were taken using confocal microscope (Leica TCS 4D, Lasertechnick, Heidelberg, Germany). Cells were counted in 8 to 10 areas each in the periphery (0.5-µm area from the limbus) and the center (central 2-µm area) of the cornea in a masked fashion using an epifluorescence microscope (model E800; Nikon, Melville, New York) at ×40 magnification. The mean number of cells were obtained by averaging the cell number in the 8 to 10 areas studied. Cell number was compared using 1-way analysis of variance (ANOVA), followed by pairwise comparisons adjusted for multiple comparisons by the least significant difference method. P values less than .05 were deemed statistically significant.

RNA ISOLATION, REVERSE TRANSCRIPTASE–POLYMERASE CHAIN REACTION, AND REAL-TIME POLYMERASE CHAIN REACTION

Total RNA was isolated from the cornea and conjunctiva (2 pooled corneas per group and 6 pooled conjunctivae per group) using Trizol (Invitrogen, Carlsbad, California, catalog No. 15996-026) for tissue homogenization and 70% ethanol for RNA precipitation, followed by extraction and purification using RNeasy Microkit (Qiagen, Valencia, California, catalog No. 74004). RNA was stored at −80°C until further use. The first strand complementary DNA (cDNA) was synthesized from 300 ng of total RNA using SuperScript III Reverse Transcriptase (Invitrogen, catalog No. 18080) per manufacturer’s protocol. Real-time polymerase chain reaction (PCR) was performed with FAM-MGB dye-labeled predesigned primers (Applied Biosystems, Foster City, California) for IL-1α (catalog No. 4329586), tumor necrosis factor α (TNF-α) (Assay ID Mm99999068_m1), GAPDH (Mm99999915_g1), IL-2 (Mm00801778_m1), IL-9 (Mm00443239_m1), IL-6 (Mm00461901_m1), IL-10 (Mm00439616_m1), and interferon γ (IFN-γ) (Mm00801778_m1) per manufacturer’s pro-
RESULTS

CLINICAL AND MOLECULAR SIGNS OF DRY EYE

Compared with day 0 (mean [SD] score, 1.3 [1.5]), corneal fluorescein staining scores were significantly higher at day 2 (5.4 [2.13]), day 5 (8.4 [1.2]), and day 10 (7.9 [3.6]) (Wilcoxon test, P=.01, n=8). No significant difference was found between groups at day 2, day 5, or day 10. Thus, dry eye induction led to a significant increase in staining that remained steadily elevated through day 10.

The normal cornea has a resident population of bone marrow–derived immature (MHC Class II−CD80−CD86−) CD11b+ antigen presenting cells (APCs) that acquire MHC Class II in response to inflammation. Induction of dry eye for 10 days increased the CD11b+ cell number in the periphery by 44% (mean [SEM], 240 [23.2] vs 345.8 [15], P=.02, n=3) and the center by 45% (183.4 [20.2] vs 265.5 [27.8], P=.09, n=3). MHC Class II expression by CD11b+ cells, an important marker for the cells’ maturation and T-cell stimulatory capacity, was increased by 104% in the periphery (75.1 [8.2] vs 152.9 [33.7], P=.07, n=3) and 146% in the center (30.4 [6.5] vs 74.8 [13.6], P=.04, n=3) of the dry eye cornea.

Corneal and conjunctival expression of proinflammatory cytokines IL-1α and TNF-α, was increased in dry eye relative to the normal eye (Figure 1 and Figure 2). However, expression of IL-1β and IFN-γ and IL-2 cytokines (IL-4, IL-6, and IL-10) was not detected in the cornea. On the contrary, the conjunctiva showed increased expression of IL-6 (14.5-fold), IL-2 (4.9-fold), IL-10 (97.6-fold), and tumor necrosis factor α (TNF-α), and IFN-γ indicates interferon-γ.

IFN-γ (16.3-fold), and IL-10 (97.6-fold) (Figure 2). IL-4 expression was not increased.

CORNEAL FLUORESCEIN STAINING IN DRY EYE TREATED WITH FA FORMULATIONS

Two days after dry eye induction, eyes were randomized to receive 1 mL of ALA, LA, combined ALA and LA, or vehicle or no eye drops. Corneal fluorescein staining scores were measured at days 5 and 10. Only ALA-treated eyes showed a sustained and significant decrease in staining compared with the untreated and vehicle control groups at both days 5 and 10 (Figure 3). At day 5, all the treatment groups showed a significant decrease in staining compared with the untreated group. However, only ALA-treated eyes showed a significant decrease compared with the vehicle (45%, P=.04); no significant difference was noted between the eyes treated...
with LA, combined ALA and LA, and vehicle. At day 10, only the ALA-treated eyes showed a significant decrease in the corneal fluorescein staining compared with the vehicle (62%, \(P = .02\)) and untreated controls (71%, \(P = .007\)). No difference was seen between the eyes treated with vehicle, LA, and combined ALA and LA and untreated eyes at day 10 (Figure 3).

### Enumeration of CD11b+ Monocytes in Eyes Treated with FA Formulations

The number of CD11b+ cells was found to be significantly decreased (\(P = .03\)) in ALA-treated eyes in the center of the cornea as compared with the untreated group and the vehicle, LA, and combined ALA and LA groups (Figure 4 and Figure 5). In the periphery, there was no significant difference between vehicle and ALA groups, although ALA treatment showed a significant decrease compared with untreated eyes (\(P = .001\)) (Figure 4). Treatment with ALA decreased the cell number by 37% (periphery) and 42% (center) compared with the untreated group and 21% (periphery) and 37% (center) compared with the vehicle. None of the other groups showed a significant difference in corneal cell number compared with the vehicle.

### Corneal and Conjunctival Expression of IL-1α and TNF-α in Eyes Treated with FA Formulations

Among-group comparisons showed that only ALA treatment persistently decreased corneal and conjunctival expression of IL-1α and TNF-α at days 5 and 10 compared with untreated eyes and eyes treated with vehicle, LA, and combined ALA and LA (Figure 6 and Figure 7). The conjunctival expression was only studied at day 10.
since higher level of these cytokines was seen in the cornea at day 10. Only ALA-treated eyes showed significant decrease in IL-1α expression compared with untreated corneas at day 10 (P = .04), significant decrease in TNF-α expression compared with untreated (P = .02) and vehicle-treated corneas (P = .04) at day 5, and a decreased trend at day 10 (P = .07). Expression of TNF-α in ALA-treated conjunctivae was significantly decreased at day 10 compared with untreated eyes (P = .004) and a downward trend was also seen in IL-1α expression. No significant difference was seen between the untreated eyes and eyes treated with vehicle, LA, or combined ALA and LA in either IL-1α or TNF-α expression.

The ALA-treated eyes showed a significant reversal in corneal epithelial damage, manifested by decreased fluorescein staining as compared with the untreated eyes and eyes treated with vehicle, LA, or combined ALA and LA. The exact mechanism of corneal epithelial repair in the ALA-treated eyes is unknown but could theoretically be mediated directly by ALA or its metabolites, EPA and DHA. In healthy individuals, nearly 5% to 10% of dietary ALA is converted sequentially to EPA and DHA by delta-5 and delta-6 desaturase enzymes. Human corneal epithelial cells express the enzyme 15-lipoxygenase (ALOX15), and the endogenous formation of neuroprotectin D1 (NPD1), a novel DHA-derived ALOX15 product, has been reported in the murine cornea. Topical NPD1 application increases the re-epithelization rate in a mouse corneal wound model. Thus, endogenous production of NPD1 from topically administered ALA may be one of the mechanisms for reversing corneal epitheliopathy in DES.

At the molecular level, dry eye induction leads to a persistent increase in corneal expression of IL-1α and TNF-α. These cytokines are important mediators of inflammation implicated in the pathogenesis of corneal ulceration, uveitis, and corneal transplant rejection. Produced constitutively in the corneal epithelium and on release by injury or death, IL-1α can up-regulate TNF-α release and its own autocrine production. Tumor necrosis factor α has been implicated as an important mediator of pathogenesis in DES. Elevated gene expression of IL-1, IL-6, IL-8, and TNF-α in the conjunctival epithelium and a higher tear concentration of IL-1 has been reported in patients with DES.

Of the formulations tested, only ALA treatment was effective in decreasing the corneal and conjunctival expression of IL-1α and TNF-α. Because these cytokines are released early in response to epithelial cell damage and are also released by activated macrophages, the epithelial repair and decreased macrophages infiltration in the ALA-treated cornea may account for the decreased...
cytokine expression. Dietary ALA has been shown to decrease endotoxin-induced macrophage production of TNF-α. Healthy humans, when fed an ALA-rich diet, have shown to suppress IL-1β and TNF-α production by 30%. However, the precise mechanism of this suppression is not yet understood.

Our study showed a nearly 100-fold increased expression of IL-10 in dry eye conjunctiva. Interleukin 10 is produced by activated macrophages and some lymphocytes. The 2 major activities of IL-10 are to inhibit IL-1 and TNF production by macrophages and to inhibit the accessory function of macrophages in T-cell activation through reduced expression of MHC Class II. Consequently, IL-10 inhibits both innate and T-cell-mediated immunity. The enhanced IL-10 expression may represent a regulatory mechanism in the ocular surface to promote quiescence and maintain normal homeostasis.

Our study showed the novel finding of corneal infiltration by mature MHC Class II–expressing APCs in dry eye. The normal central cornea has a resident population of CD45– bone marrow–derived cells that are uniformly of a highly immature (MHC Class II–CD80–CD86–) phenotype and acquire high expression of maturation markers in response to inflammation, thereby enhancing their capacity to stimulate T-cell–mediated responses. The vast majority of these resident cells are CD11b+ and of a monocyte/macrophage lineage. Up-regulation of HLA-DR is evident with confocal microscopy, and Don Pottle assisted with real-time PCR, Qiang Zhang, MD, assisted with immunohistochemical staining, and Johnson and Johnson Vision Care, Inc, and the Sjögren’s Syndrome Foundation.

In summary, our study shows the beneficial effect of ALA omega-3 FA topical application in reversing the signs and symptoms of dry eye. The use of these fatty acids in topical formulations to treat dry eye and potentially other inflammatory ocular surface conditions, would allow more flexibility in dosing without the accompanying systemic, in particular gastrointestinal, adverse effects that can be seen with oral intake of these fatty acids. Further studies are clearly indicated to optimize dosing and formulations that are maximally effective.

Submitted for Publication: April 26, 2007; final revision received June 27, 2007; accepted July 4, 2007.

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Financial Disclosure: Dr Schaumberg has served as a consultant to Vistakon and Johnson and Johnson. Dr Dana has served as a consultant to and received research support from Vistakon and Johnson and Johnson. Drs Rashid, Schaumberg, and Dana are listed as coinventors on the patent application for “compositions and methods for treating eye disorders and conditions.”

Funding/Support: This study was supported in part by Johnson and Johnson Vision Care, Inc, and the Sjögren’s Syndrome Foundation.

Additional Information: Sandra Michaud, PhD, assisted with real-time PCR, Qiang Zhang, MD, assisted with immunohistochemical staining, and Don Pottle assisted with confocal microscopy.

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