Aging is associated with progressive cell senescence, as well as the irreversible impairment of physiological tissue and organ function. At the ocular surface, the wide array of changes that occur with aging may significantly impair an individual’s quality of life. Anatomical and physiological changes that occur with aging include progressive atrophy of the lacrimal glands, keratinization of the Meibomian gland ducts, alterations in tear quality and quantity, as well as formation of conjunctival folds. Furthermore, aging has been associated with decreased corneal nerve fiber density, diminished frequencies of goblet cells, and alterations to hormone signaling and immune homeostasis (resulting in a higher incidence of autoimmune diseases in the elderly). In light of the plethora of anatomical and physiological changes that occur with aging, as well as the fact that age-related disorders (e.g., dry eye disease) are associated with increased inflammatory proteins in the tears, it is perhaps unsurprising that aging itself is associated with altered tear composition.

Given that tear proteins are critically involved in preserving metabolic and immune homeostasis of the ocular surface, these proteins have attracted attention as potential diagnostic indicators. Gradual changes in cytokines, chemokines, as well as growth and tissue remodeling factors have been observed with normal aging, and it has been proposed that alterations in these components may explain the age-related anatomical and physiological changes observed at the ocular surface. In the setting of chronic ocular inflammatory disease, the overexpression of cytokines and growth factors, as well as altered expression of matrix metalloproteinases (MMPs) and tissue inhibitors of metalloproteinases (TIMPs), have been implicated in driving inflammation and fibrotic remodeling of the ocular surface tissues. These observations suggest that tear protein composition data might be used to identify pathological molecules that drive disease, and accordingly, may represent the first steps toward the development of targeted therapeutic strategies.

We further characterized the alterations in tear protein composition that occur with aging. In particular, we evaluated/selected pro- and anti-inflammatory molecules, as well as tissue remodeling factors, that have been identified as key mediators of ocular surface pathology.

**Methods**

**Study Population**

A total of 76 consecutive volunteers older than 18 years were enrolled from December 2014 to June 2015. Subjects were
divided into three age groups (young, 18–40; middle-aged, 41–60; and old, >60). Participants with a history and/or signs of ocular surface disease, contact lens wear, systemic disease (including malignancies, metabolic diseases, psychiatric diseases), or pregnancy were excluded from the study. Furthermore, patients taking medications (either systemic or topical) at examination were excluded. All experimental procedures were performed in accordance with guidelines established by the Association for Research in Vision and Ophthalmology and adhered to the tenets of the Declaration of Helsinki concerning human subjects. The procedures for patient recruitment, tear sampling, and biochemical analysis were reviewed and approved by the intramural ethical committee (University Campus Bio-Medico, Rome, Italy). All participants provided written informed consent to proceed to conjunctival imprint and tear sampling.

**Ocular Surface Disease Index (OSDI) Questionnaire**

An OSDI questionnaire (Allergan, Inc., Irvine, CA, USA) was completed by each subject to provide a brief screening of ocular discomfort. USD grading was as follows: normal (0–12 points), mild (13–22 points), moderate (23–32 points), or severe (33–100 points).

**Tear Sampling and Handling**

Subjects underwent late morning or early afternoon non-anesthetized tear collection via the eye-flush procedure, as described previously. Briefly, the sampling procedure involved topical ocular administration of 30 μL sterile balanced salt solution (BSS; Alcon Laboratories, Inc., Fort Worth, TX, USA) and prompt tear collection by means of a sterile individually-wrapped plastic micropipette (PBI Intl., Milan, Italy). Tear samples were mixed with a cocktail of protease inhibitors (Pierce Biotechnology, Rockford, IL, USA) and stored at −20°C pending biochemical analysis. Sample delivery to the laboratory or analysis was conducted using an isothermal cage (CryoCooler; Starlab Int GmbH, Ahrensburg, Germany).

**Total Protein Analysis**

All samples were subjected to total protein analysis. Tear volume was recalculated according to the guidelines of the procedure, adjusting for a dilution factor, as described previously. Following centrifugation at 16,000g for 10 minutes, samples were diluted at a ratio of 1:2 in cold lysis buffer (50 mM Tris-HCl, 150 mM NaCl, 1 mM EDTA, 0.1% Nonidet P-40, 1 mM, NaF and 1 mM PMSF; pH 7.5). Following this, the samples were quickly sonicated (VibraCell; Sonics, Newtown, CT, USA) and clarified by centrifugation (12500g/7 min). The total protein quantification was done (3 μL/tear

<table>
<thead>
<tr>
<th>Groups</th>
<th>Subjects</th>
<th>Age, Range</th>
<th>Mean Age*</th>
<th>Sex, F/M</th>
<th>OSDI†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>76</td>
<td>19–93</td>
<td>44/32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Young</td>
<td>35</td>
<td>19–40</td>
<td>27.60 ± 6.39</td>
<td>21/14</td>
<td>11.01 ± 6.95</td>
</tr>
<tr>
<td>Middle-aged</td>
<td>23</td>
<td>41–60</td>
<td>50.17 ± 5.49</td>
<td>15/8</td>
<td>11.94 ± 13.47</td>
</tr>
<tr>
<td>Elderly/old</td>
<td>18</td>
<td>61–93</td>
<td>62.62 ± 3.70</td>
<td>8/10</td>
<td>16.12 ± 7.43</td>
</tr>
</tbody>
</table>

* Data are mean ± SD.
† OSDI score (0–100 points) was calculated according to the Allergan® suggestions and clustered as follows: normal, score 0–12; mild, score 13–22; moderate, score 22–32; severe, score 33–100.
sample) using a digital A1000 Nanodrop spectrophotometer equipped with the A280 program (Celbio, Milan, Italy). Protein electrophoresis (30 μg total proteins heated in loading buffer at 75°C/5 min) was conducted under reducing conditions (4%–12% precast resolving SDS-PAGE mini gels; 130 V/frontline; MiniProtein3 apparatus; Bio-Rad Laboratories, Inc., Hercules, CA, USA). Electrophoresed proteins were transferred to Hybond-membranes (0.22 μm; GE Healthcare, Buckinghamshire, UK), under semi-dry conditions (13 V/45 min; Trans-Blotting apparatus; Bio-Rad), and stained with a Reversible Protein Stain Kit (Pierce Biotechnology, Rockford, IL, USA). Images were digitally captured using 1D Kodak Image Software (Kodak, Tokyo, Japan), quantified, and exported as 8-tiff-based files for figure assembly in Adobe Photoshop 7.0 (Adobe Systems, Inc., San Jose, CA, USA). Samples that overexpressed albumin, IgG or fibronectin bands were pretreated with a bead-based depletion kit (GE Healthcare).21

**Chip-Based Array**

For analysis, 24 samples were tested, including young (n = 10), middle-aged (n = 8), and old (n = 6) protein extracts. The samples were selected randomly from patients with normal OSDI values. Each glass slide included 14 identical subarrays containing 60 preselected protein candidates assembled in customized G-series arrays (Ray-Biotech, Norcross, CA, USA). Candidates were selected retrospectively based on previous investigations by our laboratory20,22–25 and others,26–28 and were grouped as follows: pro/anti-inflammatory (cytokines, chemokines, and adhesion molecules and neurotrophins), tissue remodeling factors (MMPs), tissue-specific inhibitors (TIMPs), fibrogenic and angiogenic factors, and other soluble receptors/proteins. Briefly, equal quantities of protein extracts (350 ng/mL) were hybridized into array-wells and the antigen-antibody immunoreaction, including incubation and washing conditions, was conducted according to a standard procedure (Ray-Biotech). Spin-dried glass-slides were scanned in a GenePix 4400 Microarray platform (Molecular Devices LLC, Sunnyvale, Silicon-Valley, CA, USA). The specific acquisition area (array/spot) was first selected manually and then automatically adjusted for size, brightness, and contrast by the software. Normalized Fluorescent Intensity (FI) data were calculated by the GenePix Pro 6.0 software (Axon; Molecular Devices). Inter-assay normalizations were guaranteed by the presence of multiple internal controls for each subarray. The minimum sensitivity ranged between 3.8 and 56 pg/mL.

**Western Blotting and ELISA**

All samples were subjected to Western blotting analysis for the appropriate validations. Briefly, SDS-PAGE was blocked in 5% BSA-TBS (TBS, 20 mM Tris–HCl and 150 mM NaCl, pH 7.5) and immunoblotted with anti-human monoclonal or polyclonal antibodies specific for IL-8, IL-6, and MIP3β (respectively, MAB208, MAB206, and AF361; all from R&D Systems, Minneapolis, MN, USA), and regulated on activation, normal T cell expressed and secreted protein (RANTES; ab9679; Abcam, Cambridge, MA, USA). Antibodies were diluted in 0.5% TX-TBS at 0.1–1 μg/mL final concentration. The labeling step with species-specific POD-conjugated antibodies (at least 1:10000; raised in donkey; Jackson ImmunoResearch Europe Ltd, Suffolk, UK) and the developing steps with ECL-based chemiluminescence kit (West Femto Sensitivity Substrate; Pierce, Rockford, IL) were performed according to standard procedures. An immunoblot-specific signal was acquired with the 1D Image Station Analyser (Kodak, Tokyo, Japan). Data were saved as 8-bit TIFF files and exported to be shown after Adobe Photoshop CS3 assembly (Adobe Systems, Inc.). For IL-8, ELISA also was performed according to manufacturer’s instructions (DY208 duo-set ELISA kit; R&D Systems).

**Impression Cytology and Goblet Cell Staining**

In representative volunteers (n = 9; n = 3/group), conjunctival imprint at the bulbar temporal conjunctiva was performed (Millicell; 0.22 μm membranes; 13 mm diameter; Millipore, Burlington, MA, USA) in the presence of topical anesthesia (Novesina; Novartis Farma, Origgio, VA, USA), according to a standard procedure.29 Imprints were fixed (Bio-Fix spray; Bio-Optica, Milan, Italy) and processed for PAS staining, to visualize...
goblet cells (Bio-Optica). Stained membranes were removed from the plastic support (Millicell) and mounted on glass slides. Images were acquired at the Eclipse Ci microscope equipped with the NIS Elements Image software for optic field light transmission acquisition (Nikon, Tokyo, Japan).

**Statistical Analysis**

Statistical analyses were conducted using the SPSS 15.0 statistic package (SPSS, Inc., Chicago, IL, USA) and scatter/histogram panels were produced by Prism software (GraphPad, San Diego, CA, USA). The nonparametric Kolmogorov-Smirnov and Shapiro-Wilk tests assessed the Gaussian distribution of data. For chip array analysis, the specific FI averages (mean ± SD) were calculated from replicates (2 spots) of nonpooled tear samples. FI values were normalized by subtracting the background signal estimated by the software (Axon; Molecular Device). A P value ≤ 0.00083 with fold-changes >2 for 60 targets was considered significant in protein-array analysis with a Bonferroni’s correction (0.05/60), while a P value ≤ 0.05 was considered significant in nonparametric analysis using the Wilcoxon test.

**FIGURE 3.** Biochemical variables and aging (II). Correlation coefficients between age and respectively IL-3 (P < 0.05), TNF-α (P < 0.05), IL-2, and IL-21 fold-changes. (A) An opposite tendency was detected for MIP-3β (B).

<table>
<thead>
<tr>
<th>Age vs.</th>
<th>Rho</th>
<th>pValue</th>
</tr>
</thead>
<tbody>
<tr>
<td>IL3</td>
<td>r= 0.4350</td>
<td>p=0.0336</td>
</tr>
<tr>
<td>TNF-α</td>
<td>r= 0.4194</td>
<td>p=0.0413</td>
</tr>
<tr>
<td>MIP-3β</td>
<td>r= -0.3940</td>
<td>p=0.0568</td>
</tr>
<tr>
<td>IL2</td>
<td>r= 0.3817</td>
<td>p=0.0657</td>
</tr>
<tr>
<td>IL21</td>
<td>r= 0.3530</td>
<td>p=0.0906</td>
</tr>
</tbody>
</table>

**FIGURE 4.** Array validation analysis. Biomarkers having significant changes (multiparametric analysis corrected for Bonferroni test) were subjected to Western blotting. The IL-8 (A), IL-6 (C), RANTES (D), and MIP-3β (E) protein expressions in tears. Below each histogram (OD), the related SDS-PAGE (two per group). Expected protein size is shown adjacent to each immunoblot.
with age. Furthermore, the positive correlations between age and IL-3, TNFα, MIP-3β, IL-2, and IL-21 are detailed in Figure 3A.

An increasing trend also was observed for IL-2 and IL-21 with age. In contrast, a decreasing trend was found for MIP-3β expression (the scatter plot is shown in Fig. 3B).

To further delineate the effects of aging on tear composition, the tear print samples were categorized according to the following age groups: young (18–40 years, 10 subjects), middle-aged (41–60 years; eight subjects), and old (>60 years; six subjects; Table). ANOVA analysis coupled to Bonferroni post hoc was used for multiple comparisons (F = 6.11 – Df = 21 – Dfd = 1259; P < 0.0001) and confirmed: (1) increased IL-8 (P < 0.001), IL-6 (P < 0.001), and MMP-1 (P < 0.01) protein levels in tears from the old group relative to the young group; (2) increased IL-8 (P < 0.001), IL-6 (P < 0.01), and MMP-1 (P < 0.05) protein levels in tears from the old group compared to the middle-aged group; and finally (3) elevated IL-7 (P < 0.01) protein levels in tears from the middle-aged group compared to the young group. Western blot analysis corroborated the IL-8 (Fig. 4A), IL-6 (Fig. 4B), RANTES (Fig. 4C), and MIP-3β (Fig. 4D) array-outcomes. IL-8 was further quantified by ELISA analysis, thereby confirming a strong association between IL-8 and aging, as shown in Figure 5A. The volcano plot indicating the cytokines of interest is shown in Figure 5B.

ANOVA analysis also identified an increase in IL-7 expression in the middle-aged group with respect to old (P < 0.001) and groups (P < 0.05) young. No significant correlation was observed between IL-7 and age factor (P = 0.7410). Finally, an increased protein tear-print MI of array outputs demonstrated inverse correlation with decreased goblet cell number at conjunctival impression cytology (respectively in young, Figs. 6A, 6B; middle-age, Figs. 6C, 6D; and old, Figs. 6E, 6F subgroups).

**RESULTS**

The characteristics of the study population are summarized in the Table. As depicted in Figure 1, the protein arrays contained 60 potential candidates clustered as follows: pro/anti-inflammatory factors (cytokines, chemokines, adhesion molecules, neurotrophins) and tissue remodeling mediators (MMPs and TIMPs; fibrogenic and angiogenic factors). Analysis of Pearson correlation coefficients identified 8 of 60 protein candidates that were observed to vary significantly with aging. As shown in Figure 2, the expression of IL-8 (r = 0.7248; P < 0.0001; Fig. 2A), IL-6 (r = 0.5451; P = 0.0059; Fig. 2B), and RANTES (r = 0.5371; P = 0.0082; Fig. 2C) were correlated...
RANTES with age, which is suggestive of low-grade inflammation (IL-8, IL-6, and RANTES) and dynamic tissue remodeling (IL-6) being more common among the elderly population.

Aging is associated with cellular senescence and widespread tissue dysfunction. Our data are consistent with the increased prevalence of chronic, low-grade inflammation of the ocular surface among the elderly population. Biochemical factors may function to trigger or perpetuate inflammation, as observed in dry eye disease and other autoimmune disorders. Interestingly, our data showed a correlation between age and TNFα/IL-3 as well as IL-2/IL-21, cytokines that are involved in sustaining T helper-mediated immune responses. Specifically, IL-3 (from activated T cells) contributes to immune homeostasis and host defense by modulating the activity of various immune effectors (dendritic cells, granulocytes, monocytes, and mast cells), either alone or in collaboration with other cytokines. IL-2 is known primarily for driving the proliferation of activated T cells, and IL-21 is recognized for its role in Th17 immunity. Yet, both of these cytokines exert broad pleiotropic functions that modulate the activities of immune cells (including T, B, and NK cells). It is possible that IL-2 and IL-21 contribute toward age-associated immune dysregulation, which is observed as increased autoimmunity among the elderly, but also to impaired host defense against infectious insults. MMP-1 has been shown previously to be elevated during ocular surface inflammation. Our data demonstrated a positive correlation between age and MMP-1 expression in the tears of subjects, further suggesting that a state of chronic, low-grade ocular surface inflammation may be more prevalent among the elderly population. Interestingly, the negative correlation that we observed between aging and MIP-3β does not seem to be consistent with published data indicating that the recruitment of leukocytes is increased in aged tissues.

Categorizing the volunteers by age (46% young, 30% middle-age, and 23% old) allowed us to confirm the previously observed trends in IL-8, IL-6, and RANTES expression. Moreover, comparisons between the age categories unveiled a selective increase in IL-7 expression in the middle-age relative to the young groups. The increased IL-7 expression in middle-age may have additional implications for immune homeostasis and tissue remodeling, due to the capacity of IL-7 to inhibit TGF-β production and upregulate SMAD7. The absence of a significant difference in VEGF expression between the old and young groups is notable, in light of the persistence of corneal angiogenic privilege with age. Interestingly, given the association of conjunctival goblet cell loss and ocular surface inflammation, our data (Fig. 6) suggest an increased protein tear-print MI of array outputs in aged subjects, that
correlated inversely with goblet cell number at conjunctival impression cytology.

A limitation of this study is that neuromediators (such as VIP, NPY, CGRP, and SP) and BDNF, NT-4, and NGF were not evaluated by our protein-array platform. Given the importance of these factors in the context of age-related nerve degeneration and neuroinflammation, further investigation of their expression is required.22,23,25

Life expectancy is increasing worldwide, and age-related ocular surface disorders can markedly reduce human quality of life.3,51 A high-quality tear film is a major determinant of ocular surface well-being.33 Physiological cell senescence, together with environmental stressors and epigenetic factors (sunlight, VDT, natural/artificial climate, topical drugs, surgery, infections, diseases) may contribute toward dysregulation of ocular surface immunity and predispose to tissue damage.52,53 Understanding the changes in pro-/anti-inflammatory mediators and tissue remodeling factors that occur with aging will enable the development of novel diagnostic tests based on biomarkers. Moreover, defining these critical proteins may permit the design of targeted, personalized artificial tear substitutes.

Acknowledgments

The authors thank Fondazione Roma for continuous intramural support.

Supported in part by the Italian Ministry of Health and by Regione Lazio under the project MaBIOS-Kit (FILAS-RU-2014-1112; AM, GE).

Disclosure: A. Micera, None; A. Di Zazzo, None; G. Esposito, None; R. Longo, None; W. Foulsham, None; R. Sgrulletta, None; S. Bonini, None

References


