Clinically Relevant Immune-Cellular Metrics of Inflammation in Meibomian Gland Dysfunction

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PURPOSE. To determine the reliability and clinical relevance of in vivo confocal microscopy (IVCM)-based immune-cellular metrics of palpebral conjunctival inflammation in meibomian gland dysfunction (MGD).

METHODS. Sixteen MGD patients and 13 reference controls included in this cross-sectional, retrospective study, had an ocular surface exam, symptom assessment (Ocular Surface Disease Index questionnaire [OSDI]), and palpebral conjunctival IVCM imaging. Bland-Altman analyses, intraclass correlation coefficient (ICC), Lin’s concordance correlation coefficient (ρc), receiver operating characteristic (ROC) analyses, and correlations were performed. Clinical outcome measures were symptom severity (OSDI scores), tear break-up time (TBUT), and corneal fluorescein staining (CFS grade).

RESULTS. Compared to controls, patients with MGD had variable symptom severity (average OSDI score: 48.3 ± 7.6, P = 0.0008, range: 8.3–85.42), shorter TBUT (6.8 ± 0.9 seconds, P = 0.002), comparable corneal staining (0.31 ± 0.19, P = 0.20), and greater conjunctival inflammation (epithelial immune cells [EIC]: 477.8 ± 54.2 vs. 125.3 ± 17.2 cells/mm², P < 0.0001; intraglandular immune cells [IGIC]: 41.9 ± 3.3 vs. 20.3 ± 7.3, P < 0.01). Immune-cellular metrics had high inter- and intraobserver agreement (ICC: 0.83–0.99; Cronbach’s α: 0.85–0.94; ICC, and Cronbach’s α: 0.85–0.97), while both EIC and IGIC correlated inversely with TBUT (rC = −0.47, −0.45, P < 0.05), and had high accuracy in detecting inflammation (ROC area under the curve [AUC]: 0.97 and 0.89, P < 0.001).

CONCLUSIONS. EIC and IGIC are increased in highly symptomatic patients with MGD that have minimal corneal staining, and correlate with symptoms and clinical signs. EIC and IGIC may provide reliable and clinically relevant metrics of inflammation.

Keywords: MGD, inflammation, confocal microscopy, dry eye

The recently highlighted role of inflammation in the pathogenesis of meibomian gland dysfunction (MGD) makes the detection and assessment of inflammation vital for the evaluation of patients with dry eye disease (DED) and assessment of therapeutic efficacy of anti-inflammatory therapies in these patients. The development of objective cellular metrics becomes especially necessary since an estimated 40% of patients with MGD either are asymptomatic,1 or have symptoms but an unremarkable clinical examination, forming the complex and challenging group of dry eye patients with symptom–sign disparity.2-5 Our group recently studied such MGD patients that presented with persistent symptoms of discomfort in the presence of a normal slit-lamp examination after treatment with gland expression procedures for MGD. We demonstrated that these MGD patients with refractory symptoms despite an improved examination had clinically non-apparent inflammation of the palpebral conjunctiva, evident on laser scanning in vivo confocal microscopy (IVCM).3 Compared to MGD patients that had improved symptoms following anti-inflammatory treatment, patients with refractory symptoms had a 3-fold increase in palpebral conjunctival epithelial immune cell density (EIC),5 despite the absence of apparent clinical signs on slit-lamp examination, furthering our understanding of the pathogenesis underlying symptom–sign disparity in MGD patients.

Among the quantitative methods currently available for evaluating the palpebral conjunctiva and meibomian glands, only IVCM allows direct visualization6-8 and quantitation of immune cells (ICs). Recently, Zhou and Robertson9 used immunohistochemistry and IVCM of human eyelid sections to assess the validity of previously published papers to date. They demonstrated that previous quantitative and qualitative IVCM studies that presumably analyzed meibomian glands to establish diagnostic utility, classifications and grading of MGD, correlations to signs and symptoms, and meibomian gland changes in systemic and other ocular diseases,10-24 were actually studying rete ridges at the dermal-epidermal junction of the free lid margin, which also have an acinar appearance on
Further, Knop and colleagues\textsuperscript{25} had shown similar findings through hematoxylin and eosin sections and IVCM when describing the lid margin, focusing on dendritiform cells in superficial epithelia and around the acinar-like cross sections of the rete ridges, not the meibomian glands.\textsuperscript{6,10–14,16–18,26} In addition to one qualitative report of meibomian glands within the substantia propria.\textsuperscript{8} Therefore, in alignment with the evidence, we believe that this study now demonstrates quantitative, layer-by-layer assessment of inflammation in both the palpebral conjunctiva and meibomian glands. Consequently, this is, to our knowledge, the first detailed report on the diagnostic utility, reliability, and clinical relevance of IVCM-based palpebral conjunctival epithelial, stromal (substantia propria), and meibomian glandular metrics of inflammation.

In the current study, we developed, validated, and correlated quantitative novel immune-cellular metrics for the assessment of inflammation, which is often nonobvious in MGD. We developed and tested a 10-metric panel focused on layer-by-layer quantitation of palpebral conjunctival inflammation in MGD by IVCM. We established inter-and intraobserver agreement, consistency, reproducibility, and concordance for each of the 10 in vivo metrics. Clinical relevance of these parameters was assessed by correlation with clinical signs (tear break-up time [TBUT], corneal fluorescein staining grade [CFS]), and symptom severity (Ocular Surface Disease Index score [OSDI]). Palpebral conjunctival IVCM-based immune-cellular metrics of inflammation proved to be consistent, reproducible, accurate, and clinically relevant in MGD. Palpebral conjunctival EIC and intraglandular immune cells (IGIC) correlated directly with symptom severity (OSDI) and inversely with tear film stability (TBUT). Receiver operating characteristic (ROC) analyses illustrated very good to excellent accuracy of EIC and IGIC in detecting eyelid inflammation. EIC and IGIC may therefore serve as clinically relevant endpoints of inflammation in evaluating MGD patients for palpebral conjunctival inflammation and monitoring their response to treatment in clinical trials and clinical practice.

\textbf{Materials and Methods}

\textbf{Study Design and Patient Population}

We conducted a retrospective, cross-sectional, observational, controlled study, investigating both eyes of 16 MGD patients seen at the Cornea Service of the Massachusetts Eye and Ear Infirmary (MEEI), Boston, Massachusetts, between 2011 and 2013 as part of routine care. This study was approved by the MEEI institutional review board (IRB), was Health Insurance Portability and Accountability Act (HIPAA) compliant, and adhered to the tenets of the Declaration of Helsinki. One eye of 13 healthy, asymptomatic, age- and sex-matched individuals from our normative research database were used as reference controls.

With respect to inclusion criteria, patients included in this study had a clinical diagnosis of MGD based on clinical symptoms of ocular discomfort and either lid findings on clinical slit-lamp examination (irregular lid margin, telangiectasia, Meibomian Glands Yielding Liquid Secretion score) or a TBUT of less than 10 seconds (s). Refractory MGD patients with persistent symptoms despite clinical improvement in TBUT after prior treatment (TBUT > 10 s) who were referred to us were also included.

As to exclusion criteria, neuropathic corneal pain was ruled out in all MGD patients, both clinically (positive response to topical anesthetic in any patient with complaints of corneal pain), and through imaging of corneal subbasal nerves using IVCM. Hence, our study population did not have neuropathic corneal pain, which can be a confounding factor in the assessment of patients with symptom-sign disparity.

All reference controls in this study were healthy, asymptomatic individuals who had no CFS and a TBUT > 10 s. All controls were drawn from an IRB-approved prospective normative study database that enrolled healthy subjects after having a complete history and ocular examination comprising CFS, TBUT, anterior segment examination, applanation tonometry, and corneal sensation. Only subjects who had an unrewardable examination were recruited to the database.

All associated imaging was performed at the MEEI Ocular Surface Imaging Center (OSIC). Medical charts and study forms were reviewed for medical history and details of anterior segment slit-lamp examination findings including TBUT and CFS. Patient symptom severity scores from the OSDI questionnaire were also reviewed.\textsuperscript{27–29} Two masked observers analyzed IVCM images of the palpebral conjunctiva acquired as part of routine patient care.

\textbf{IVCM}

Laser scanning IVCM (Heidelberg Retinal Tomograph 3 with the Rostock Cornea Module [HRT3/RCM]; Heidelberg Engineering GmbH, Heidelberg, Germany) had been used to capture layer-by-layer en face images of the palpebral conjunctival epithelium, using the method described below. The HRT3/RCM IVCM provided a field of view of 400 × 400 μm, with a lateral resolution of 1 to 2 μm and an axial resolution of 4 μm.

Both eyes of all MGD patients and one eye of healthy asymptomatic controls were topically anesthetized using one drop of 0.5% proparacaine hydrochloride (Alcan; Alcon, Fort Worth, TX, USA) per eye followed by application of hydroxypropyl methylcellulose 0.3% gel (GenTeal Gel; Alcon Laboratories, a Novartis Company, Fort Worth, TX, USA). Prior to imaging each patient, the base of a sterile, disposable polymethylmethacrylate cap (Tomo-Cap; Heidelberg Engineering) was filled halfway with hydroxypropyl methylcellulose 0.3% (GenTeal Gel) and mounted on the exterior of the HRT3/RCM optical lens. To enhance optical coupling, a drop of hydroxypropyl methylcellulose 0.3% was also placed on the external surface of the Tomo-Cap at its tip. The seated patient’s chin and forehead were carefully and comfortably placed firmly against the chin and forehead rests. The tip of a cotton swab was placed on the skin of the lower eyelid, parallel to and below the lid margin. With gentle downward pressure on the cotton swab, the lower eyelid was everted and the camera was manually advanced until the gel on the tip of the Tomo-Cap made contact with the palpebral conjunctival mucosa. The camera was moved as far laterally as possible while maintaining contact with the palpebral conjunctiva. Once epithelial and goblet cells of the palpebral conjunctiva were visualized, the depth of the scan was set to 0 μm (reference depth) and scanning was started in sequence mode, which provided a dynamic movie mode of up to 100 frames at variable depths and an acquisition speed of 30 frames/second.

At each point (lateral, central, medial) along the palpebral conjunctival images were acquired, starting at a depth of 5 μm (epithelium) and advancing deeper into the tissue up to a depth of 200 μm into the substantia propria. Transition from the epithelium into the substantia propria was identified by the presence of a fibrous, amorphous background punctuated with clusters of circular acinar-like structures and vessels. With further advancement into the substantia propria,
glandular ductules were visualized. Image of the palpebral conjunctiva at depths greater than 200 μm could not be visualized. Once the inferolateral region of the everted lower eyelid had been imaged, the depth of focus was receded back to the epithelium, and the lens with the Tomo-Cap was glided medially to the center of the everted lower eyelid. Before beginning image acquisition at the new position, reference depth was reset to 0 μm and the region was imaged again. Upon completing imaging of the central palpebral conjunctiva, the lens was advanced to the most medial (nasal) region possible without losing contact with the palpebral conjunctival epithelium. At the new position, the reference depth was reset to 0 μm upon visualization of the epithelial cells, before proceeding to image the deeper layers. Once the three regions (lateral, central, medial) at the inferior edge of the everted eyelid in the horizontal plane had been surveyed, the lens was advanced superiorly along the conjunctiva, moving toward the fornix, and positioned at the lateral margin in the new horizontal plane. The steps described above were repeated until the majority of the everted lower eyelid had been imaged. A total of 5 to 12 sequence scans of 100 images each were acquired per eyelid and stored on a network computer.

Patients who could tolerate eversion of the upper eyelid with a cotton swab received an additional drop of topical anesthetic and hydroxypropyl methylcellulose 0.5% gel. The same procedure described for lower eyelid imaging above was repeated until the majority of the everted lower eyelid had been imaged. A total of 5 to 12 sequence scans of 100 images each were acquired per eyelid and stored on a network computer.

**Image Analysis**

Two masked observers made all the measurements using ImageJ software (https://imagej.nih.gov/ij/; provided in the public domain by National Institutes of Health, Bethesda, MD, USA). A single observer selected representative images for analysis. The criteria for selection of images included good focus for structures of interest, visualization of the structure(s) of interest, absence of motion artifacts, and without regions of overexposure or hyperreflectivity that may make differentiating structures difficult. Three images per parameter per eye were analyzed for each subject totaling quantitative analysis of 1320 images. For patients, measurements from both eyes of each patient were averaged to represent a single sample. All results were reported as a mean of the measurements made by both the observers and expressed as mean ± standard error of mean (SEM) unless noted otherwise.

Palpebral conjunctival images were analyzed for EIC, stromal IC (SIC), IGIC, and gland ductular luminal dimensions (Table 1; Fig. 1). For en face images, the whole frame (400 × 400 μm) was analyzed, counting all cells within the frame and expressing density as the number of cells/mm². For oblique images, immune cells were counted only within the region of interest (ROI). The ROI was selected and measured using the polygon tool in ImageJ. Immune cells were identified as hyperreflective, polymorphous (dendritiform, non-dendritiform, spindle-shaped) cellular structures within the epithelium and substantia propria, ranging in size from 5 to 20 μm.50 Intraductular immune cell analysis was performed on all glandular ductules within each frame that had visible hyperreflective, intraluminal content. Luminal occlusion by IGIC within ductules was reported as mean percentage occlusion. Ductular dimensions of internal luminal width (W) and length (L) were measured for both glandular ductules with (IGIC+) and without (IGIC−) visible hyperreflective, intraluminal

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**Table 1. IVCM-Based Metrics for Quantitative Evaluation of Palpebral Conjunctival Epithelium, Substantia Propria, and Glands in MGD-Associated Ocular Inflammation**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit of Measurement</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epithelial immune cell density, EIC</td>
<td>Cells/mm²</td>
<td>Location and extent of inflammation; status of immune activation on the surface of palpebral conjunctiva</td>
</tr>
<tr>
<td>Stromal immune cell density, SIC</td>
<td>Cells/mm²</td>
<td>Location and extent of inflammation; status of immune activation in the substantia propria of palpebral conjunctiva</td>
</tr>
<tr>
<td>Periglandular immune cells, PGIC</td>
<td>No. of cells within 20-μm radius around the gland</td>
<td>Location and extent of inflammation; status of immune activation in the substantia propria of palpebral conjunctiva</td>
</tr>
<tr>
<td>Intraglandular immune, IGIC</td>
<td>% of glandular ductule luminal area occupied by immune cells</td>
<td>Extent and infiltration of inflammation; degree of plugging and occlusion of glandular ductules with visible immune cellular content</td>
</tr>
<tr>
<td>Luminal width of ductules with visible intraglandular content, IGIC+*W</td>
<td>μm</td>
<td>Morphologic alterations in glandular architecture</td>
</tr>
<tr>
<td>Luminal length of ductules with visible intraglandular content, IGIC+*L</td>
<td>μm</td>
<td>Morphologic alterations in glandular architecture</td>
</tr>
<tr>
<td>Thickness of hyperreflective luminal ring in ductules with visible intraglandular content, IGIC+</td>
<td>μm</td>
<td>Reactive proliferative or atrophic activity within glandular ductule</td>
</tr>
<tr>
<td>Luminal width of ductules without visible intraglandular content, IGIC−*W</td>
<td>μm</td>
<td>Morphologic alterations in glandular architecture</td>
</tr>
<tr>
<td>Luminal length of ductules without visible intraglandular content, IGIC−*L</td>
<td>μm</td>
<td>Morphologic alterations in glandular architecture</td>
</tr>
<tr>
<td>Thickness of hyperreflective luminal ring in ductules without visible intraglandular content, IGIC−</td>
<td>μm</td>
<td>Reactive proliferative or atrophic activity within glandular ductule</td>
</tr>
</tbody>
</table>

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*(W)* and *L* refer to the width and length of the ductules, respectively.
content. All ductules within each frame were analyzed. Thickness of the internal luminal ring (r) lining the ductule was calculated for each of these ductules per frame as described below.

**Epithelial Immune Cell (EIC) Density.** In the analysis of EIC (Fig. 1A), particular attention was paid to avoid counting goblet cells and epithelial cells that typically appear larger and less hyperreflective than immune cells. All cells were counted within an en face frame, or within the ROI in oblique frames, and reported as cells/mm².

**Stromal Immune Cell (SIC) Density.** In the analysis of SIC (Fig. 1B), particular attention was paid not to count immune cells within acinar epithelium and lumens of ductules, blood and lymphatic vessels, as they were not the interstitial matrix of the palpebral conjunctiva. All cells were counted within an en face frame, or within the ROI in oblique frames, and reported as cells/mm².

**Periglandular Immune Cells (PGIC).** All cells within a 20-μm radius around the acinar epithelium for each acinus were counted and averaged per frame (Fig. 1C). Careful attention was paid not to include intraepithelial immune cells located within the acinar epithelium (Fig. 1C). Results were reported as the mean number of cells per 20-μm radius of the external acinar epithelium.

**Intraglandular Immune Cells (IGIC).** The intraluminal area occupied by cells within each glandular ductule and the total luminal area of each glandular ductule (Fig. 1D) were measured for all ductules within every frame and expressed as mean percentage occlusion.

**Luminal Width of Ductules With (IGIC*) and Without (IGIC/C) Visible Intraglandular Content.** The internal luminal width (W) of every glandular ductule with and without visible, hyperreflective, intraglandular content within each frame was measured (Figs. 1E, 1F), averaged, and reported in microns. The caliper was placed perpendicularly to that used for measuring internal length (L) of the ductules.

**Luminal Length of Ductules With (IGIC*) and Without (IGIC/C) Visible Intraglandular Content.** The internal luminal length (L) of every glandular ductule with and without visible, hyperreflective, intraglandular content within each frame was measured (Figs. 1E, 1F) averaged, and reported in microns. The caliper was placed perpendicularly to that used for measuring internal width (W) of the ductules.

**Thickness of Internal Luminal Hyperreflective Ring (r) in Ductules With (IGIC*) and Without (IGIC/C) Visible Intraglandular Content.** After placing calipers measuring the internal luminal length of the glandular ductule (L), the same caliper was extended at each end to encompass the external length (EXT-L) of the ductule to ensure that the plane of measurement was constant (Figs. 1E, 1F). To compute thickness of the internal luminal hyperreflective ring (r), presumed to be ductular epithelium, this equation was applied: (external length – internal length)/2. These measurements were performed for all glandular ductules within each frame, with and without visible intraglandular content. The results were averaged per frame and reported in microns.

**Statistical Analysis**

Normality of data was determined using the Shapiro-Wilk normality test based on which either parametric (Student’s independent samples 2-tailed t-test) or nonparametric tests (Mann-Whitney U test) were applied for intergroup comparisons. Effect size was computed for all parameters that had a
normal distribution (parametric) using Cohen’s d, Glass’s delta, and Hedges’s statistics. Post hoc power was determined for all the parameters. Sex-matching was evaluated by Fisher’s exact test. A P value less than 0.05 was considered statistically significant.

Interobserver reliability was determined for each of the 10 imaging parameters by the Bland-Altman analysis and plots (agreement), \( r^2 \) intraclass correlation coefficient of agreement (ICC\(_a\), reproducibility), Cronbach’s alpha (\( \alpha \), internal consistency), and Lin’s concordance correlation coefficient (\( r_c \), reproducibility with bias correction). ICC\(_a\) was computed using a 2-way mixed model and stepped for agreement. For LCCC, a prewritten syntax (http://vassarstats.net/clin1.html; in the public domain) to calculate the parameters. Sex-matching was evaluated by Fisher’s exact test. A P value less than 0.05 was considered statistically significant.

Table 2. Demographics and Clinical Characteristics of Controls and Patients With MGD

<table>
<thead>
<tr>
<th>Age, y, Mean ± SEM</th>
<th>Sex, M/F</th>
<th>OSDI Score Mean ± SEM (Range)</th>
<th>Tear Film Osmolarity, mOsm/L, Mean ± SEM</th>
<th>TBUT, s, Mean ± SEM</th>
<th>CFS Grade Mean ± SEM</th>
<th>n, Patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controls 43.25 ± 3.99</td>
<td>6:7</td>
<td>12.00</td>
<td>303.8 ± 4.2</td>
<td>10.97 ± 0.69</td>
<td>0</td>
<td>13</td>
</tr>
<tr>
<td>MGD 54.63 ± 3.85</td>
<td>2:14</td>
<td>49.48 ± 6.97 (8.30–85.42)</td>
<td>305.9 ± 6.0</td>
<td>6.84 ± 0.93</td>
<td>0.51 ± 0.19</td>
<td>16</td>
</tr>
<tr>
<td>( P ) value</td>
<td>0.051</td>
<td>0.09</td>
<td>0.0008</td>
<td>0.99</td>
<td>0.20</td>
<td>39</td>
</tr>
<tr>
<td>( U ) value</td>
<td>NA</td>
<td>NA</td>
<td>13</td>
<td></td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

Both controls and patients with MGD were age- and sex-matched. \( P \) value for the difference in sex ratio between the groups represents the \( F \) statistic for Fisher’s exact test. MGD patients had a shorter TBUT (seconds, \( P = 0.002 \)), and a wide range of symptom severity the mean of which was significantly higher than that for asymptomatic, healthy controls (OSDI score; \( P = 0.0008 \)). There were no differences in the tear film osmolarity \( (P = 0.20 \) and CFS grade (NI grading system, \( P = 0.99 \)) between the two groups. Data are reported as mean ± SEM. A \( P \) value less than 0.05 was considered statistically significant.

Qualitative Assessment of MGD-Associated Palpebral Conjunctival Inflammation by IVCM

Qualitatively, there were several notable differences between the palpebral conjunctival tissue and glands of healthy controls, and patients with MGD (Fig. 2). As compared to controls (Fig. 2A), the palpebral conjunctiva in patients with MGD had greater infiltration of EIC (Fig. 2B), seen as an increased number of hyperreflective polymorphous structures. Similarly, progressing to the deeper layers of the palpebral conjunctiva, in comparison to controls (Fig. 2C), patients with MGD (Fig. 2D) had increased speckling of the substantia propria, caused by an increase in SIC. Fibrosis was also seen around acini. Some ICs were found immediately adjacent to the external acinar epithelia (Figs. 2E, 2F). These PGICs were distinct from intraepithelial immune cells previously described in the literature, which lie specifically within the epithelium of the acini; such intraepithelial immune cells were also observed in our sample of MGD patients (Fig. 2F). Of particular interest was the presence of hyperreflective, nonnecrotic, circular structures within the lumens of conjunctival glandular ductules (presumed meibomian glands) both in controls, and patients with MGD (Figs. 2G, 2H). This intraglandular content was increased in MGD patients as compared to controls, with greater occlusion and distension of the ductular lumen in MGD (Fig. 2H).

In Vivo Metrics of Palpebral Conjunctival and Glandular Inflammation in MGD Using IVCM

Immune-Cellular Metrics. Of the four metrics (EIC, SIC, PGIC, IGIC) devised to quantify immune cells in the palpebral conjunctival epithelium, substantia propria, and glands, EIC and IGIC demonstrated the most significant differences between healthy controls and MGD (Table 3); EIC and IGIC had very large effect sizes (EIC: 2.0–5.5, IGIC: 0.9–1.5), and an observed power of 100%. As compared to controls (EIC: 123.3 ± 17.2 cells/mm\(^2\), IGIC: 20.33 ± 7.3%), MGD patients had a near 4-fold increase in epithelial immune cells (EIC: 477.8 ± 54.2 cells/mm\(^2\), \( P < 0.0001 \), and a 2-fold increase in gland intraductular occlusion (IGIC: 41.9 ± 3.5%, \( P < 0.01 \)). In comparison to controls (PGIC: 0.9 ± 0.4 cells/20-μm radius), PGIC nearly
doubled in MGD (PGIC: $2.6 \pm 0.5$ cells/20-µm radius, $P = 0.07$, power: 67%), and this increase approached but did not achieve statistical significance. Among the glandular ductules without visible cellular content, those in MGD had larger luminal dimensions as compared to healthy controls (IGIC $/C_0^W$: $12.3 \pm 0.9$ vs. $6.4 \pm 3.1$ µm, $P = 0.03$; IGIC $/C_0^L$: $24.1 \pm 1.4$ vs. $14.7 \pm 5.9$ µm, $P = 0.05$). These dimensions also had large effect sizes (IGIC $/C_0^W$: 0.9–1.2, IGIC $/C_0^L$: 0.7–1.2; Table 3) and an observed power of 99% to 100%. Furthermore, when all glands with visible IGIC (controls and MGD patients combined) were compared to all glands without visible IGIC (controls and MGD patients combined), it was clear that glands with occluded meibomian gland ductules leading to altered ductular dimensions in MGD (H). Scale bars: 100 µm.

**FIGURE 2.** IVCM of the palpebral conjunctiva in controls and patients with MGD-associated palpebral conjunctival inflammation. Representative en face in vivo confocal micrographs of healthy controls (A, C, E, G) and patients with MGD (B, D, F, H), illustrating increased immune cells in the palpebral conjunctival epithelium (B) and stroma with periacinar fibrosis (D), periglandular cells around the acinar epithelium (F), and increased occlusion of presumed meibomian gland ductules leading to altered ductular dimensions in MGD (H).

**Inflammation in MGD**

**IOVS** | December 2018 | Vol. 59 | No. 15 | 6116

**Inter- and Intraobserver Agreement and Reliability of IVCM-Based Metrics of Inflammation.** Bland-Altman analysis (Table 4) showed that for all immune-cellular metrics (EIC, SIC, PGIC, IGIC), the mean difference (bias) between interobserver measurements was small (bias: 6.9%–14.9%, EIC $< IGIC < SIC < PGIC$) and not statistically significant ($P = 0.13–0.43$). Bland-Altman plots (Fig. 3) illustrated good interobserver agreement for each of these parameters except PGIC, where the 95% LoA were too large to be acceptable for this parameter. All immune cellular measurements were without proportional bias. EIC, SIC, and IGIC had excellent internal consistency ($\alpha$: 0.93–0.97; Table 4), and high combined inter- and intraobserver agreement ($ ICC_a$: 0.93–0.97; Table 4). $pq_c$, which corrects for chance among interobserver measurements, confirmed that among the immune-cellular metrics, EIC, SIC, and IGIC had the strongest reproducibility free of chance (EIC $> SIC > IGIC$, $pq_c$: 0.86–0.94; Table 4), whereas interobserver reproducibility for PGIC was considered substantial but not perfect ($pq_c$: 0.72; Table 4).

**Glandular Metrics.** Bland-Altman analyses (Table 4) showed that the mean difference (bias) between interobserver measurements for glandular ductule luminal width and length was significant for the smaller ductules without IGIC (IGIC $/C_0^W$,
Diagnostic Utility of EIC and IGIC in Detecting Inflammation

ROC plots and analyses (Fig. 5) suggested that EIC and IGIC were excellent to very good parameters to detect inflammation, respectively. The ROC plots had large AUCs for both EIC (AUC: 0.97, P < 0.001, 95% CI, 0.91–1.00) and IGIC (AUC: 0.89, P = 0.001, 95% CI, 0.75–1.00), indicating very good to excellent diagnostic accuracy for palpebral conjunctival and glandular inflammation. Additionally, ARs were also high for both EIC (AR: 0.94) and IGIC (AR: 0.79). ROC plot analysis with estimations for specificity, sensitivity, PPV, NPV, LR+, LR− and accuracy, provided potential cutoffs for EIC and IGIC to determine the presence of palpebral conjunctival tissue inflammation. EIC > 195.8 cells/mm² provided high sensitivity (0.94, 95% CI 0.68–0.99) and specificity (0.92, 95% CI 0.59–0.99), high PPV (0.94, 95% CI 0.68–0.99) and NPV (0.92, 95% CI 0.59–0.99), and a strong ability to rule in (LR+: 11.25, 95% CI 1.72–73.78) and rule out (LR−: 0.07, 95% CI 0.01–0.4616) the presence of palpebral conjunctival epithelial inflammation. IGIC ≥ 21.2% had excellent sensitivity (100%, 95% CI 0.75–1.00) with good specificity (78%, 95% CI 0.40–0.96), good PPV (0.88, 95% CI 0.62–0.98) and excellent NPV (1.00, 95% CI 0.56–1.00), and a strong ability to rule in (LR+: 4.50, 95% CI 1.33–15.28) the presence of intraglandular inflammation. DOR and J, both of which are independent of disease prevalence and measure the discriminative power of a test, were high for both EIC (DOR: 1.3, J: 0.85) and IGIC (DOR: 1.7, J: 0.78), suggesting their potential use as discriminative tests for ruling in or ruling out inflammation.

DISCUSSION

In an era of decelerated dry eye drug development, inconsistent clinical trial endpoints, and frustration among ophthalmologists and optometrists caring for patients with symptom-sign disparity, there is a growing need for objective, reliable, and clinically relevant measures of detecting, assessing, and monitoring disease severity in patients with ocular surface disease, such as DED or MGD. Since inflammation contrib-
Table 4. Intraclass Correlation Interclass Correlation

<table>
<thead>
<tr>
<th>Metric</th>
<th>Bias, Mean</th>
<th>SD</th>
<th>95% CI</th>
<th>P Value</th>
<th>% Bias</th>
<th>LoA</th>
<th>Cronbach's α</th>
</tr>
</thead>
<tbody>
<tr>
<td>EIC, cells/mm²</td>
<td>23.76</td>
<td>21.83</td>
<td>12.88, 4.05</td>
<td>47.19, 38.37</td>
<td>0.91, 0.98</td>
<td>&lt;0.001</td>
<td>0.87, 0.97</td>
</tr>
<tr>
<td>SIC, cells/mm²</td>
<td>141.76</td>
<td>189.29</td>
<td>0.13</td>
<td>7.21</td>
<td>0.93, 0.99</td>
<td>0.91</td>
<td>0.99</td>
</tr>
<tr>
<td>PGIC, % occlusion</td>
<td>2.12</td>
<td>61.10</td>
<td>2.6, 6.8</td>
<td>0.53</td>
<td>6.3</td>
<td>30.11, 21.36</td>
<td>0.89, 0.97</td>
</tr>
<tr>
<td>IGIC, % occlusion</td>
<td>4.79</td>
<td>8.92</td>
<td>1.21</td>
<td>0.27, 1.67</td>
<td>0.97</td>
<td>0.13, 0.80</td>
<td>0.95</td>
</tr>
</tbody>
</table>

The MGD patients in our study were interesting in that they had symptoms of dry eye with minimal to no corneal staining despite shortened TBUT. The lack of correlation of any palpebral conjunctival metrics of inflammation with CFS, yet moderately strong and significant correlations with OSDI and TBUT, suggests that corneal epithelial integrity is not necessarily affected by palpebral conjunctival inflammation. Therefore, in a symptomatic patient with MGD, an absence of corneal staining does not automatically rule out underlying clinically nonapparent palpebral conjunctival inflammation. Thus, evaluation by IVCM may aid in the assessment of symptomatic MGD patients with an incongruent corneal slit-lamp examination, which can then be differentiated from dry eye patients with symptom–sign discordance due to a central neurologic process. These findings emphasize that outcome measure selection needs to be based not only on the type of DED but on imaging-based metrics as well.
Imaging-based biomarkers of inflammation could provide additional information facilitating characterization of the cellular milieu in the tissue. This insight into the inflammatory state of the tissue may potentially enhance patient care by way of appropriate patient stratification for anti-inflammatory treatment regimens and measurement of therapeutic efficacy of drugs as part of both routine care and clinical trials in ocular surface disease. Among the many issues in selection of clinical endpoints and biomarkers for clinical trials have been the overbearing presence of inconsistent reproducibility, and lack of standardization and validation. Looking toward imaging outcome measures as surrogates of clinical disease is a promising approach. The past decade has seen a steady rise in the application of imaging biomarkers across specialties within ophthalmic clinical trials.48 While this trend is encouraging, a systematic, nationwide strategy focusing on establishing centralized image reading centers or the use of artificial intelligence needs to be institutionalized. Such establishments will help to ensure consistent methodology for standardization of metrics and subsequent validation of potential imaging biomarkers that can be stratified for types of ocular surface disease.

Furthermore, we believe that imaging biomarkers EIC and IGIC may be promising surrogate biomarkers of inflammation in MGD since they fulfill the criteria for surrogate biomarkers.49-53 Not only do EIC and IGIC correlate with the clinical endpoints of symptom severity (OSDI) and clinical sign (TBUT), which is necessary but not sufficient,50 but they are also directly involved in the pathophysiological cascade of inflammation that is involved in the pathogenesis in MGD.54,55 An interesting observation made in the course of this study was the morphology of cellular content within the glands; the cells appeared round, and consistent with both size and appearance of lymphocytes,30 highly suggestive of T cells. The role of T cell–mediated immunity in the pathogenesis of a subset of dry eye disease, aqueous-deficient dry eye disease (ADDE), is strongly established in the literature,56-58 providing a cue for the role of adaptive immunity in possibly other subsets of DED as well. Nien and colleagues34 reported the presence of CD45⁺ inflammatory cells in the substantia propria of the palpebral conjunctiva with infiltration of the acinar epithelium in patients with MGD. Similarly, we observed frequent speckling of acinar epithelium, presumably immune cells. More recently, Reyes et al.59 identified neutrophils...
**FIGURE 4.** Correlation of immune-cellular metrics with symptom severity and clinical signs in MGD-associated palpebral conjunctival inflammation. $r_s$ was used to determine the strength of correlation between in vivo confocal immune cell parameters that were significantly altered in MGD, and both clinical symptom severity (OSDI scores) and TBUT. Both palpebral conjunctival EIC (A, C) and percentage occlusion of presumed meibomian IGIC (Figs. 3B, 3D) showed direct correlation with OSDI (A, B), and inverse correlation with TBUT (C, D). $P < 0.05$ was considered statistically significant. $N$ represents the number of subjects available with both measurements.

### Table 5. Clinical Relevance of IVCM-Based Metrics of Palpebral Conjunctival Epithelial and Glandular Inflammation

<table>
<thead>
<tr>
<th>Correlated Parameters</th>
<th>Correlation Coefficient, $r_s$</th>
<th>Coefficient of Determination, $r^2$</th>
<th>$P$ Value</th>
<th>Observed Power, %</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EIC, cells/mm$^2$–OSDI score</td>
<td>0.49</td>
<td>0.24</td>
<td>0.03</td>
<td>61.3</td>
<td>21</td>
</tr>
<tr>
<td>IGIC, % occlusion–OSDI score$^*$</td>
<td>0.48</td>
<td>0.23</td>
<td>0.05</td>
<td>49.1</td>
<td>17</td>
</tr>
<tr>
<td>PGIC, cells/20-μm radius–OSDI score</td>
<td>0.43</td>
<td>0.18</td>
<td>0.09</td>
<td>37.0</td>
<td>16</td>
</tr>
<tr>
<td>EIC, cells/mm$^2$–TBUT</td>
<td>−0.47</td>
<td>0.22</td>
<td>0.02</td>
<td>68.3</td>
<td>26</td>
</tr>
<tr>
<td>IGIC, % occlusion–TBUT</td>
<td>−0.45</td>
<td>0.20</td>
<td>0.04</td>
<td>55.2</td>
<td>22</td>
</tr>
<tr>
<td>PGIC, cells/20-μm radius–TBUT</td>
<td>−0.21</td>
<td>0.04</td>
<td>0.36</td>
<td>13.7</td>
<td>21</td>
</tr>
<tr>
<td>EIC, cells/mm$^2$–CFS grade</td>
<td>0.29</td>
<td>0.08</td>
<td>0.21</td>
<td>22.3</td>
<td>19</td>
</tr>
<tr>
<td>IGIC, % occlusion–CFS grade</td>
<td>0.39</td>
<td>0.15</td>
<td>0.15</td>
<td>26.8</td>
<td>15</td>
</tr>
<tr>
<td>PGIC, cells/20-μm radius–CFS grade</td>
<td>0.01</td>
<td>0.00</td>
<td>0.96</td>
<td>4.2</td>
<td>14</td>
</tr>
<tr>
<td>TBUT–OSDI score</td>
<td>−0.56</td>
<td>0.31</td>
<td>0.007</td>
<td>77.9</td>
<td>22</td>
</tr>
<tr>
<td>CFS grade–OSDI score</td>
<td>0.52</td>
<td>0.27</td>
<td>0.02</td>
<td>69.5</td>
<td>19</td>
</tr>
<tr>
<td>TBUT–CFS grade</td>
<td>−0.55</td>
<td>0.30</td>
<td>0.01</td>
<td>71.4</td>
<td>20</td>
</tr>
</tbody>
</table>

EIC, PGIC, and IGIC were correlated with symptom severity (OSDI score), tear film stability (TBUT, seconds), and corneal epithelial integrity (NEI corneal fluorescein staining grade, CFS) using $r_s$ and $r^2$. EIC and IGIC showed significant correlation with OSDI and TBUT, but not CFS. EIC and IGIC predicted up to 24% variability in OSDI scores, and 22% variability in TBUT. There was symptom–sign correlation in our study sample. Of the 15 controls and 16 MGD patients, images with glands were identified in 7 and 15 subjects, respectively.

$^*$ Correlation of IGIC with OSDI approached but did not attain statistical significance, likely due to lower observed power of 49%. $n$ represents the total number of subjects. A $P$ value less than 0.05 was considered statistically significant, which are shown in bold along with their corresponding $r_s$ and $r^2$ values.
causing obstruction of meibomian glands in a mouse model of chronic inflammation associated with ocular allergy. This finding suggests that perhaps the innate immune system plays an early role in meibomian gland inflammation, inciting the adaptive arm of the immune response through myeloid and plasmacytoid dendritic cells.

In patients with MGD, we also observed subepithelial fibrosis of the substantia propria around acini and ductules. Based on this finding and our earlier work, we hypothesized that periductular fibrosis may be a possible mechanism behind obstructive forms of MGD. This band of constriction around acinar ductules is likely broken, yielding a ‘‘pop’’ sound during meibomian gland probing, relieving the stricture. Our hypothesis has been supported by colleagues with similar findings, which has led to a new classification system for obstructive MGD. MGD is frequently seen in individuals older than 60 years, in whom it is postulated that decreased cell cycling and meibocyte differentiation with increasing age leads to glandular dysfunction. However, it appears that the process of palpebral conjunctival goblet cell loss and reduction in meibomian acinar units begins as early as the early 40s, or perhaps even earlier. This contrasts with earlier studies in which even individuals older than 70 years did not show changes in meibomian glands, ducts, and the quality of meibum.

IVCM of the palpebral conjunctiva necessitates technical training of imaging personnel, which can be time-consuming to begin with, but with experience over time it may become practical to do in an outpatient setting. In addition to technical training, careful image selection and quantitation of EIC and IGIC also require training, close monitoring, and stringent quality control, which may not be readily available at many centers with laser IVCM. Hence, there is benefit in establishing centralized national or international reading centers that can validate and standardize imaging surrogate biomarkers of ocular surface disease in addition to providing quick, accurate, and reliable imaging reports. EIC and IGIC have already been shown to be robust metrics in the detection of inflammation in patients with MGD. Our group initially reported findings of a series of five such MGD patients who were symptomatic despite an unremarkable slit-lamp examination. In a research setting, however, we believe that these in vivo metrics quantifying palpebral conjunctival epithelial and intraglandular inflammation may supersede other clinical endpoints either in the detection and grading of inflammation toward patient inclusion criteria, or, detecting response to therapy even in short-duration clinical trials. With the very large effect sizes observed for EIC and IGIC, smaller sample sizes will be required for research studies, making clinical trials much more affordable. Moreover, EIC and IGIC may also be useful in quantifying and grading severity of the inflammatory component of disease.

Our study provides validated real-world evidence for the use of EIC and IGIC in detecting palpebral conjunctival epithelial and intraglandular inflammation in evaporative DED. The next steps forward would be to test these metrics of inflammation as clinical endpoints in a randomized, controlled clinical trial targeting inflammation in MGD. It would be interesting to see if EIC, SIC, and/or IGIC may be more responsive to anti-inflammatory therapy than symptom severity and clinical signs such as CFS, TBUT, tear film osmolarity, and meibum scores. Since these are immune cellular parameters, we hypothesize that the metrics defined in our paper will respond earlier and to a larger degree than clinical tests, which are macroscopic, leading to shorter and consequently less expensive clinical trials.
Inflammation in MGD

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References