Quantitative 3-dimensional Geometry of the Aging Eyelids

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Background: Although facial aging is a well-known phenomenon, it has not been comprehensively characterized in 3 dimensions. This study introduces a novel technique for capturing periorbital structures across age groups using 3-dimensional (3D) imaging and point cloud data collection.
Methods: Forty-six white women were divided into 3 age groups: 20–39 years, 40–59 years, and 60+ years. Patients were scanned with the Canfield 3D photogrammetry system, and data files were exported to the point cloud processing software CloudCompare. Manually selected points specifying eyelid margins, creases, and 5 key periorbital features provided the basis for a fitted model and principal component analysis (PCA). Potential statistical significance across age groups was assessed for PCA values corresponding to each subject's eyelid geometry.
Results: Three tendencies emerged with respect to increasing age and eyelid anatomy: the width and height of the palpebral fissure decreases, with the width decreasing more rapidly; the depth of the lateral canthus relative to the medial canthus decreases; and the superior crease becomes more variable. Analyses of variance of PCA values across age groups show statistically significant differences between the youngest and oldest groups.
Conclusions: Three-dimensional photogrammetry enables rigorous and reliable evaluation of the aging eyelid. Results suggest age-induced changes to eyelid margin, crease, and lateral canthus positions, which have been noted anecdotally but poorly quantified until now. (*Plast Reconstr Surg Glob Open 2019;7:e2512; doi: 10.1097/GOX.0000000000002512; Published online 8 November 2019.*)

INTRODUCTION

Aging causes a change in eyelid shape with a combination of volume depletion and protrusion[1] that has not yet been quantitatively characterized in a 3-dimensional (3D) fashion. An accurate understanding of the variation in normal eyelid anatomy, especially across age groups, is essential for understanding the effects of aging and achieving optimal outcomes in periocular surgeries.

As age increases, the levator palpebrae superioris muscle and its aponeurosis, which control eyelid retraction and form the superior crease (SC), weaken due to stretching or disinsertion from the tarsal plate.[2] As a result, the superior eyelid lengthens, the crease rises, and the superior eyelid margin lowers.[2] These changes create a hollowed appearance of the orbit.[3] Other senile changes that have been described include loss of elastic fibers and increase in lymphatic vessel density and dilation within the eyelid tissue,[4–6] hypertrophy and relaxation of the orbicularis oculi muscle,[3] and herniation of orbital fat into the superior lid.[2,5] These changes increase preseptal tissue volume and cause sagging of preseptal

skin over the superior eyelid crease. Like the superior eyelid, the inferior eyelid also loses tone, usually due to laxity of the lateral canthal tendon, and becomes predisposed to ectropion with age.[2] Elastic fiber loss, lymphatic vessel dilation, and skin laxity of the inferior eyelid have also been observed.[4–6]

Quantitative data on eyelid shape particularly with respect to age have been limited by the technology available, and the field is full of contradictory data. Historically, direct anthropometry has been the gold standard of facial measurements.[7–9] Instruments such as calipers and rulers can be used to measure distances and angles between well-defined landmarks. Fezza and Massry used calipers to measure inferior eyelid length among a population of white females and found the length increases vertically with age ($P < 0.0001$).[7] Cartwright et al used metric rulers to directly measure eyelid and brow heights among a population of white participants between <1 and 60+ years. Superior eyelid crease heights increased between 21 and 40 years ($P < 0.001$) but showed no significant movement in later years.[8]

van den Bosch et al took measurements from slide projections of frontal and sagittal views.[1] They found that the palpebral fissure width increased by more than 10% between 12 and 25 years, but decreased by nearly 10% between 45 and 85 years ($P = 0.01$). The inferior eyelid sagged with age, especially in men, and the superior eyelid crease and eyebrow rose in both sexes. Of note, van den Bosch et al also found that aging did not affect the positions of the eyeball or the lateral canthus (LC).[1]

Several other researchers based eyelid measurements on frontal photographs, both digital and film.[10–12] Price et al found no statistically significant change in superior eyelid crease height or palpebral fissure length with age after controlling for race and sex.[11] In contrast, Erbagci et al found that the palpebral fissure length decreased with age ($P = 0.0001$) across their population of 100 white participants between ages 3 and 80 years.[13] Kunjur et al,[14] Cho and Glavas,[10] and Nishihira et al[12] used similar 2-dimensional (2D) photographic techniques, but analyzed potential racial and sex effects on eyelid and brow dimensions rather than changes with age. Although these studies have produced valuable data regarding horizontal, vertical, and angular displacement of the eyelid and brow, their techniques cannot quantify differences in curvatures in 3D space.

Magnetic resonance imaging (MRI) has been used to assess superior eyelid creases qualitatively. For example, Galatoire et al used sagittal T2-weighted MRI images and T1-weighted 3D images to describe the appearance of superior eyelid creases and sulci among 6 participants of varying races.[15] Researchers found that low orbital septum insertions on the levator aponeurosis and drooping orbital fat pads on MRI subjectively correlated with clinically convex appearing superior eyelid sulci. Age effects were not assessed, and quantitative geometric analysis of the crease using the MRI images was not performed.

This present study uses 3D photogrammetry to capture periocular structures and enable point cloud data collection. Analyses are performed to compare normal eyelid anatomy across 3 age categories (20–39 years, 40–59 years, and 60+ years).

METHODS

Subjects

After IRB approval, 46 white female subjects between 20 and 88 years old were recruited at Rhode Island Hospital. Subjects with known periocular pathology or trauma were excluded. The study population of 46 individuals (92 eyelids) was divided into 3 age groups: 20–39 years (16 subjects), 40–59 years (15 subjects), and 60 years and older (15 subjects).

Scanning and Data Collection

Subjects' faces were scanned with the Canfield 3D Vectra 5 pod photogrammetry system (Canfield Scientific, Fairfield, NJ, USA) in a sitting position and with a resting, forward gaze. The resulting data files were de-identified by isolating a narrow strip that extended from the glabella to the zygomatic process using the Mirror software (Canfield Scientific). The rest of the image was discarded. Data files were exported to the 3D point cloud processing software CloudCompare (open source software available at http://www.danielgm.net/cc/), and full facial data files were eliminated by converting to RGB point formats. RGB refers to a color system commonly used in computer graphics that combines red, green, and blue in varying proportions to create a full color spectrum.[16] As shown in Figure 1, 3D points were manually selected in CloudCompare to define 5 key features for each patient's right and left eye: the medial canthus (MC), LC, inferior margin (IM) midpoint, superior margin (SM) midpoint, and SC midpoint. The right and left SC, SM, and IM were also manually delineated for each subject, as shown in Figure 2. One investigator (CAF) repeated point picking for 10 randomly selected subjects to assess intraobserver variability. A second researcher (JAG) repeated the point picking process for the same 10 subjects to assess interobserver variability.

Three-dimensional Eye Model Contours

The manually selected points, which include the 5 key features and delineations described above, were used to generate 3 fourth-order polynomial curves in 3 dimensions for each subject (ie, SC, SM, and IM). Images were registered relative to each other at the MC (coordinates 0, 0, 0).

An example fitted model is shown in Figure 1, where the contours of the model are shown as colored curves: the IM (yellow), the SM (red), and the SC (cyan). To illustrate that the model accounts for the full 3D geometry of the eye, a volumetric rendering of the model, including the eyeball, iris and pupil, is shown in Figure 3. This model was generated for academic interest only, and the model was not used for data capture. The measurements for this study were taken directly from the individual facial images, without any need for scaling or manipulation.

Principal Component Analysis

The 5 key periorbital feature points were recomputed from the fitted model to improve accuracy. These key feature points provided the basis for characterizing age effects through principal component analysis (PCA). For the PCA, a multidimensional space was defined by the 3D coordinates
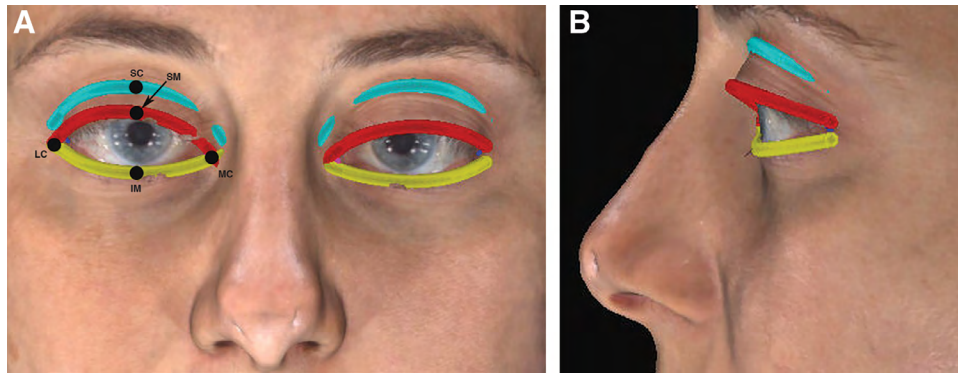
Fig. 1. A, Frontal view of the 3D eye model contours. The key features are MC, LC, IM midpoint, SM midpoint, and SC midpoint. The SC (cyan), SM (red), and IM (yellow) contours are defined by 3D polynomial curves. B, Sagittal view of the 3D eye model contours.
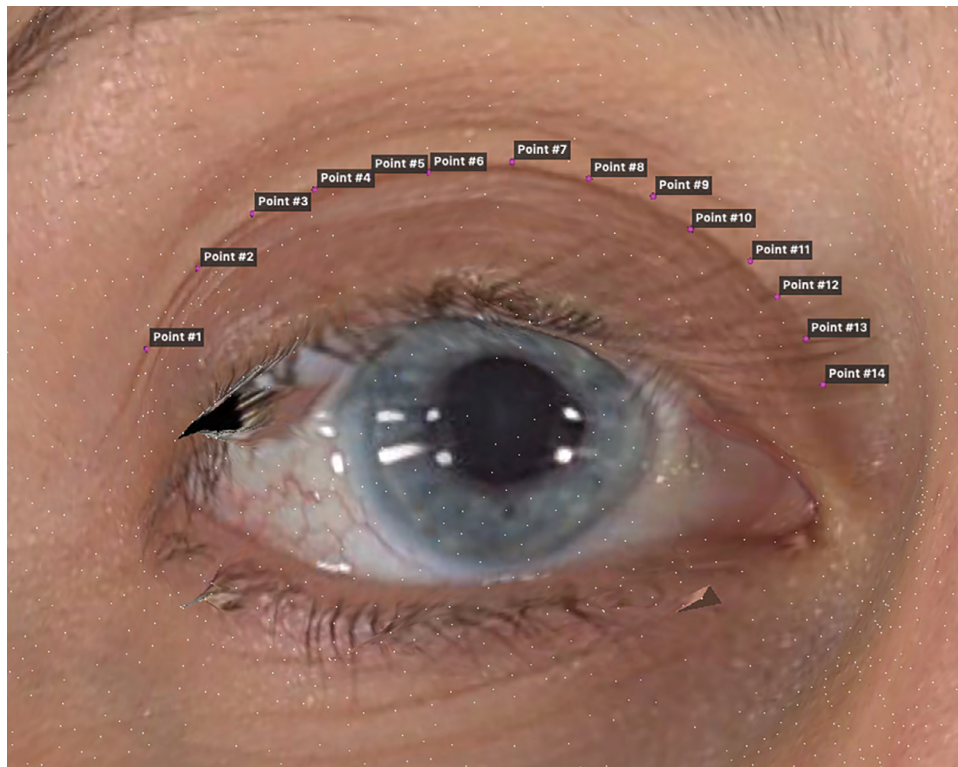

Fig. 2. A typical set of manually selected points. In this example, the SC is being delineated.

of the key periorbital features listed above, with the MC set as the origin (coordinates 0, 0, 0). Matrices describing the transformation of these multidimensional spaces across age groups were then reduced to a single principal vector for each subject that accounted for the majority of data variance. The single principal vectors describe the relative extent to which each subject's 5 key feature points vary with respect to the multidimensional spaces of all subjects. The projection of this principal vector onto each of the original eyelid dimensions revealed the sensitivity of a given periorbital feature. Lastly, a new one-dimensional coordinate was formed from the principal vector, and values (called PCA values) corresponding to each subject's eyelid geometry were extracted.

Tests of Significance

The potential statistical significance of the PCA values was assessed across age groups by analyses of variance (ANOVA), which yielded F values and associated *P* values. Statistical analyses were performed using ANOVA, a program for performing multifactor ANOVA on UNIX systems.

RESULTS

Qualitative Intergroup Contour Variation

Figure 4 demonstrates composite overlays of the 3D eye model contours within the youngest and oldest age groups, respectively. The variation from subject to subject is indicated by variation away from the MC origin. A
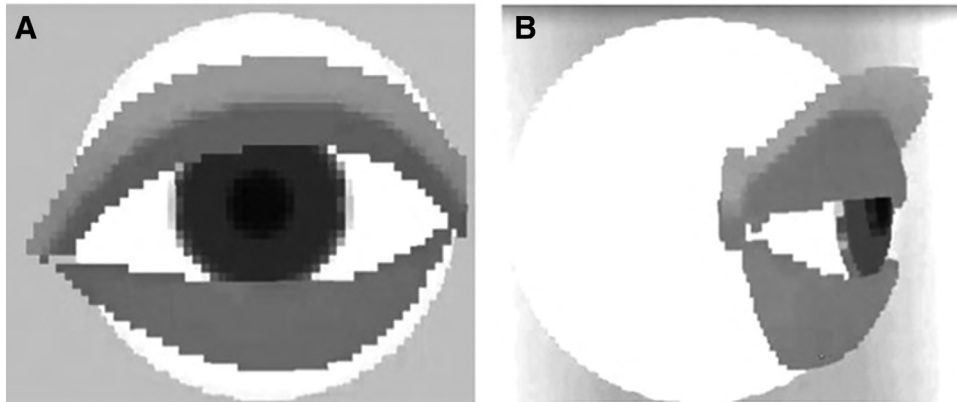
Fig. 3. A, Frontal view of the 3D volumetric eye model. Voxels are 0.5 mm on a side. The model scales with eye sphere radius. B, Sagittal view of the 3D volumetric eye model.
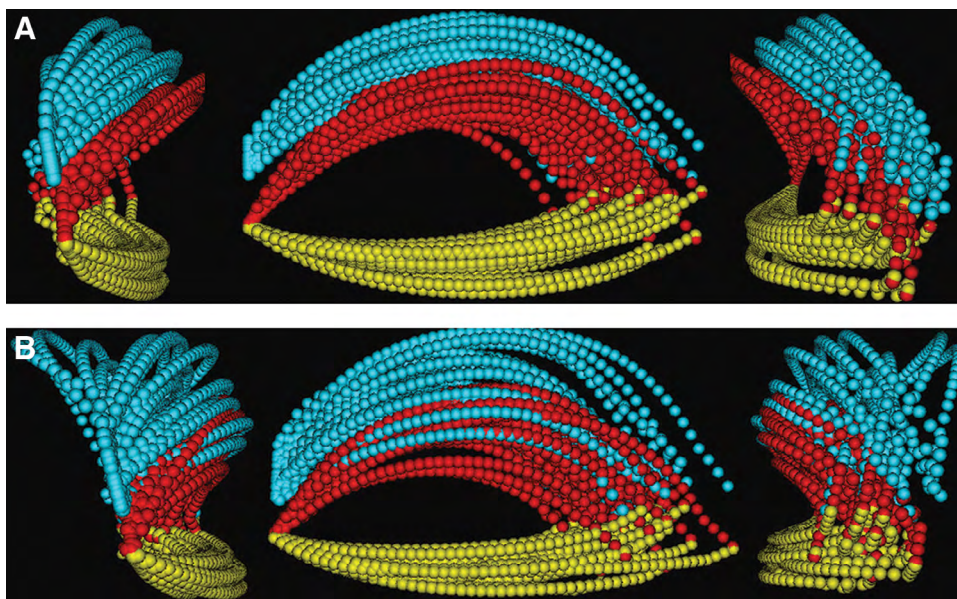

Fig. 4. A, Composite overlays of the left 3D eye contours for the youngest age group (20–30 years) centered on the MC. The superior eyelid crease is in cyan, the superior lid margin is in red, and the inferior lid margin is in yellow. The MC is registered to the 3D origin (coordinates 0, 0, 0). B, Composite overlays of the left 3D eye contours for the oldest age group (60+ years) centered on the MC. Again, the superior eyelid crease is in cyan, the superior lid margin is in red, and the inferior lid margin is in yellow. The MC is registered to the 3D origin (coordinates 0, 0, 0).

comparison of contours across age groups shows notable differences between the youngest and oldest age groups.

PCA

The sensitivities, or relative contributions to the PCA, for the periorbital features assessed in this study are given in Table 1. The more significant projections include the width between medial and lateral canthi, the height of the SC, the horizontal distance from mid-margins and mid-creases to the medial canthi, and the depth of the LC relative to the MC. A comparison of the PCA values for each subject is shown in Figure 5. The plot of Figure 5 indicates that subjects in the 60+ years age group (green) tend to have positive PCA values, whereas the 20–30 years age group (blue) tends to have negative values. The 40–50 years age group is approximately evenly spread between the 2 domains. These tendencies convey the following implications for eye geometry with increasing age, given the sensitivities in Table 1: the width and height of the palpebral fissure decreases, with the width decreasing more rapidly; the depth of the LC relative to the MC decreases; and the SC becomes more variable.

Inter- and Intraobserver Variability

In terms of repeatability, intraobserver error under the best circumstances ranged from 0 to 2.57 mm, with an average of 1.19 mm. Repeated point picking of 10 randomly selected subjects by the primary researcher

Table 1. Sensitivities of the Key Periorbital Features, Relative to the MC

	LC	SM Midpoint	SC Midpoint	IM Midpoint
Sensitivity (x, y, z)	−0.57, 0.011, 0.29	−0.32, −0.18, −0.15	−0.28, −0.46, 0.2	−0.3, 0.076, 0.029

The sensitivity of a given periorbital feature describes the contribution of that feature to the principal vector from the PCA.
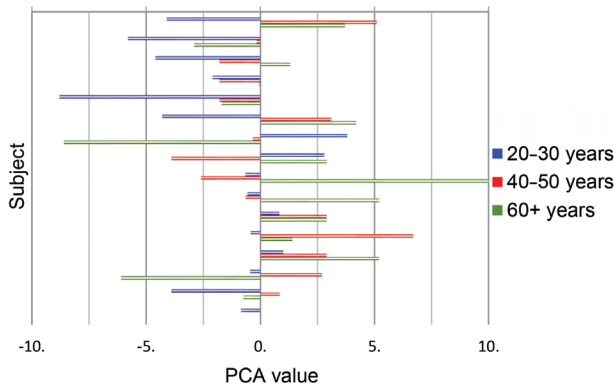

Fig. 5. The value of the PCA measure for each subject, by age category. The 60+ years group (green) tends to have positive PCA values, whereas the 20–30 years group (blue) tends to have negative values. The 40–50 years group (red) values are approximately evenly spread between the 2 domains.

yielded an error range of 0.47–3.38 mm and average of 1.35 mm. Point picking of the same 10 subjects by a second researcher yielded an error range of 0.60–4.31 mm and average of 1.78 mm.

Tests of Significance

The ANOVA F test across the 3 age groups produces an F value of 2.78, with degrees of freedom $df_i = 2$ and $df_{s2} = 43$. The corresponding P value is 0.07321. It was noted that there are 2 significant outliers contrary to the tendency for the 60+ years group to have positive PCA values (ie, −8.6 and −6.1). The data for these 2 cases are shown in Figure 6A. By comparison, the most positive PCA values for the 20–30 years age group are 3.8 and 2.8. The raw data images for these subjects are shown in Figure 6B. We describe the former 2 subjects as "youthful appearing old eyes" and the latter 2 subjects as "old appearing young eyes," primarily due to the position of the SC8.

When the 2 60+ years outliers (the "youthful appearing old eyes") were removed from the statistical test, the new F value is 5.93 with degrees of freedom $df_i = 2$ and $df_{s2} = 41$. The corresponding P value is 0.0054, indicating convincing significance that age is a major factor in the changing eyelid geometry. One other statistical comparison directly computed the F and P values for the oldest (60+ years) and youngest (20–30 years) groups. In this test, the outliers mentioned above were not removed. The F value is 3.97 with degrees of freedom $df_i = 1$ and $df_{s2} = 29$. The corresponding P value is 0.056. When an analysis was performed with the removal of the 2 60+ years outliers and the 40–50 years age group, the F value is 10.91 with degrees of freedom $df_i = 1$ and $df_{s2} = 27$. The corresponding P value is 0.0026.

DISCUSSION

This study builds on current understandings of the aging eyelid by making use of 3D photogrammetry and PCA of point cloud data. Three tendencies emerged through the PCA with respect to increasing age: the width and height of the palpebral fissure decreases, with the width decreasing more rapidly; the depth of the LC relative to the MC decreases; and the SC becomes more variable.

The corresponding P and F values for these tendencies across the 3 age groups are 0.07321 and 2.78, respectively, indicating that the result is unlikely to be caused by chance alone. Furthermore, a comparison between the youngest (20–30 years) and oldest (60+ years) age groups yields a P value of 0.056 and F value of 3.97, indicating age dependency resides mainly in the 20–30 and 60+ years groups, which is reasonable given the spread of values seen in Figure 5. Excluding the 2 60+ years group outliers produces an F value of 5.93 and P value of 0.0054, whereas excluding the 40–50 years age group and the 60+ years group outliers produces an F value of 10.91 and P value of 0.0026.

Our finding that the palpebral width decreases with increasing age is consistent with most previous studies.[18] Erbagci et al reported a gradual decrease in palpebral fissure length with increasing age among participants between the ages of 3 and 80 years.[13] van den Bosch et al found that the horizontal eye fissure lengthened by more than 10% between 12 and 25 years, but decreased by nearly 10% after 45 years.[1] In contrast, Price et al found little or no changes in palpebral fissure length with increasing age.[11]

Among those studies that found palpebral fissure shortening, most attributed it to medial drifting of the LC.[1,18,19] From a 3D perspective, medial drifting of the LC would necessitate anterior displacement as it trails along the corneal surface of the eye.[1] Our study shows the depth of the LC relative to the MC decreases with age, which coincides with van den Bosch's finding that the lateral canthal angle and the anterior corneal surface, from a sagittal view, decreases between ages 25 and 85 years.[1] These results suggest that a lateral canthopexy or canthoplasty may be more effective in restoring a youthful appearance than a lower lid shortening procedure, such as a wedge excision or Kuhnt Szymanowski procedure, which further narrows and rounds the palpebral fissure.

Results from past studies on palpebral fissure height have been more variable. Our findings that the fissure height decreases with age supports those of Lambros' qualitative analysis of animations made by layering patients' frontal photographs at various ages.[19] His more recent study that utilizes a 3D facial averaging tool similarly shows smaller lid apertures, both vertically and horizontally, among the older age group.[20] In contrast, van

Fig. 6. A, Subjects in the oldest age group (60+ years) with the 2 most negative PCA values: (left) −8.6 and (right) −6.1. B, Subjects in the youngest age group (20–30 years) with the 2 most positive PCA values: (left) 3.8 and (right) 2.8.

den Bosch et al[1] found that the height increases slightly between ages 25 and 85 years due to downward movement of the inferior eyelid margin, and Price et al[11] and Erbagci et al[13] found little or no change in palpebral height with increasing age. These varying results may be due to differences in how palpebral fissure height was measured in each study. For example, van den Bosch et al defined "height" as the sum of the pupil center to superior eyelid margin distance and pupil center to inferior eyelid margin distance;[1] Erbagci et al used the same parameters but assessed each distance (ie, superior lid to pupil center and inferior lid to pupil center) separately.[13] In contrast, Price et al defined "height" as the distance between the inferior lid margin to the superior lid margin "over the pupil" but not necessarily the pupil center.[11]

With respect to the relationship between width and height of the palpebral fissure, our finding that width decreases to a greater extent than height supports a commonly held idea that the fissure rounds out with age.[19] As Lambros explains in his qualitative analysis, the eyelids of younger eyes produce "a true almond shaped eyelid aperture."[19] In older eyes, "the lid appear[s] more fusiform" and outline a more rounded palpebral fissure.[19] Lambros' more recent 3D facial averaging study also demonstrated a wider fissure among the younger age group.[20]

Lastly, our finding that the SC becomes more variable with age likely reflects the complex changes in volume depletion and protrusion that have been qualitatively described in the past literature. Even as the SC rises with age, the superior eyelid may acquire redundant skin, fat protrusion, and lateral orbital hooding that obscure the rising crease. The ambiguous quantitative results regarding crease movement with age from studies that used 2D techniques[1,8,11] may reflect the complexity of these anatomical changes.

We argue that our current technique is capturing the visible skin fold, and the areas obscured by overhanging preseptal skin. Areas potentially affected by hooding skin, such as the lateral eyelid, would demonstrate a downward shift toward the SM, whereas areas potentially affected exclusively by muscle laxity or orbital atrophy, such as the central or medial eyelid, would demonstrate an upward shift toward the brow. This loss of uniformity of the visible SC with increasing age is an interesting clinical finding that lacks quantitative evidence. Cartwright et al hint at

this point by suggesting that the large standard of deviation among their oldest age group may be due to increased physiologic variability seen with aging.[8] Our study supports Cartwright et al's claim by offering data that quantify variability in terms of 3D shapes rather than 2D distances. At the same time, this finding reveals a limitation to our method, because we were unable to discern between the true crease and overhanging skin folds.

Another limitation to our method relates to gaze, which affects both the superior and IM positions. Subjects were asked to look at a standard target in the direction of the camera, and only images consistent with anterior gaze were used. Depending on the subjects' height, their gaze may have been slightly elevated. We expect these differences were not significant across the population.

In conclusion, this study takes advantage of 3D photogrammetry to provide a comprehensive 3D analysis of the palpebral fissure anatomy and superior eyelid crease and how they change over time. This provides normative 3D data for diagnosis and treatment goals and a quantitative tool for facial assessment. Analyses of point cloud data have revealed changes to eyelid margin, crease, and LC positions including rounding of the palpebral fissure, anterior displacement of the LC, and greater variability and retro-positioning of the superior eyelid crease.

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REFERENCES

1. van den Bosch WA, Leenders I, Mulder P. Topographic anatomy of the eyelids, and the effects of sex and age. *Br J Ophthalmol.* 1999;83:347–352.
2. Finsterer J. Ptosis: causes, presentation, and management. *Aesthetic Plast Surg.* 2003;27:193–204.
3. Lieberman DM, Quatela VC. Upper lid blepharoplasty: a current perspective. *Clin Plast Surg.* 2013;40:157–165.
4. Nagi KS, Carlson JA, Wladis EJ. Histologic assessment of dermatochalasis: elastolysis and lymphostasis are fundamental and interrelated findings. *Ophthalmology.* 2011;118:1205–1210.
5. Damasceno RW, Avgitidou G, Belfort R Jr, et al. Eyelid aging: pathophysiology and clinical management. *Arq Bras Oftalmol.* 2015;78:328–331.
6. Jacobs LC, Liu F, Bleyen I, et al. Intrinsic and extrinsic risk factors for sagging eyelids. *JAMA Dermatol.* 2014;150:836–843.

7. Fezza JP, Massry G. Lower eyelid length. *Plast Reconstr Surg.* 2015;136:152e–159e.

8. Cartwright MJ, Kurumety UR, Nelson CC, et al. Measurements of upper eyelid and eyebrow dimensions in healthy white individuals. *Am J Ophthalmol.* 1994;117:231–234.

9. Farkas LG. *Anthropometry of the Head and Face.* Raven Press; 1994.

10. Cho M, Glavas IP. Anatomic properties of the upper eyelid in Asian Americans. *Dermatol Surg.* 2009;35:1736–1740.

11. Price KM, Gupta PK, Woodward JA, et al. Eyebrow and eyelid dimensions: an anthropometric analysis of African Americans and Caucasians. *Plast Reconstr Surg.* 2009;124:615–623.

12. Nishihira T, Ohjimi H, Eto A. A new digital image analysis system for measuring blepharoptosis patients' upper eyelid and eyebrow positions. *Ann Plast Surg.* 2014;72:209–213.

13. Erbagci I, Erbagci H, Kizilkan N, et al. The effect of age and gender on the anatomic structure of Caucasian healthy eyelids. *Saudi Med J.* 2005;26:1535–1538.

14. Kunjur J, Sabesan T, Ilankovan V. Anthropometric analysis of eyebrows and eyelids: an inter-racial study. *Br J Oral Maxillofac Surg.* 2006;44:89–93.

15. Galatoire O, Touitou V, Heran F, et al. High-resolution magnetic resonance imaging of the upper eyelid: correlation with the position of the skin crease in the upper eyelid. *Orbit.* 2007;26:165–171.

16. Farkas LG, Bryson W, Klotz J. Is photogrammetry of the face reliable? *Plast Reconstr Surg.* 1980;66:346–355.

17. Pascale D. A review of RGB color spaces. http://www.babelcolor.com/index_htm_files/A%20review%20of%20RGB%20color%20spaces.pdf.

18. Hill JC. An analysis of senile changes in the palpebral fissure. *Can J Ophthalmol.* 1975;10:32–35.

19. Lambros V. Observations on periorbital and midface aging. *Plast Reconstr Surg.* 2007;120:1367–1376; discussion 1377.

20. Lambros V, Amos G. Three-dimensional facial averaging: a tool for understanding facial aging. *Plast Reconstr Surg.* 2016;138:980e–982e.