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Methodology for the construction and comparison of 3D models of the human cornea

Edouard Auvinet[1], Jean Meunier[2], Jeb Ong[3], George Durr[3], Marina Gilca[3], Isabelle Brunette[3]

Abstract— **This paper describes a methodology to build and compare 3D models (or atlases) of the cornea for specific populations. Using topography data of the anterior and posterior corneal surfaces, average and statistical variation maps are computed after registration of individual corneas on a reference sphere. With this methodology, a normal population model is constructed and compared with known eye anatomic data. Comparison of left and right eyes is also performed to see their natural symmetry. Our results demonstrate that spatial normalization is an important step for corneal atlas construction and comparison.**

I. INTRODUCTION

Medical textbook atlases are well recognized as useful tools in biology and medicine. However they represent only a single individual, not a population. Starting in the early 1980s, computerized atlases were developed for several human organs (brain, heart, lung, kidney etc.) and typically include quantitative information obtained from a set of subjects. This makes them much more representative of a given population. However, these models usually require that the individual organs be normalized or aligned to the same position, orientation and size prior to averaging to remove blurring effects [1][2]. For instance, in neuroimaging, the brain scans are normalized so that one location in one subject's brain corresponds to the same location in another subject's brain. The corneal shape is particularly important because it has a direct effect on its optical function. An appropriate 3D corneal model is therefore of great importance in the fields of ophthalmology and optometry. Traditional corneal shape analysis has evolved from subjective analysis of a target reflection (e.g. Placido disk) on the cornea to sophisticated videokeratographs or topographers that are based on light slit scanning of the cornea in combination (or not) with Placido disk automatic analysis. For instance, the Orbscan II system (Bausch & Lomb, Rochester NY) used in this study and shown in Fig.1 uses a video camera to capture the reflection of a slit of light projected on and through the cornea to calculate, by triangulation, the shape of its anterior and posterior surfaces. The shape of these surfaces is presented as topography maps (Fig. 2). The elevation (height) is usually presented with respect to a Best-Fit-Sphere. The BFS is the sphere that best fits the anterior (or posterior) surface of the cornea in the least-mean-square sense in a central region of adjustment. Elevation values above the BFS are shown with hot colors (e.g. yellow) and values under the BFS are is cold colors (e.g. blue). BFS values are in green. Notice that these systems are essentially used to study a single topography at a time. By looking at the three topographies of normal subjects shown in Fig.2, one can immediately see that one topography taken alone cannot represent the whole normal population because of normal variability between subjects. Only a few research groups have attempted to characterize a population from a set of topographies. For instance, Grzybowski et al. [3] compared the usefulness of different corneal zones for the alignment of pre- and post-LASIK topographies. This led to low variability in or near the registration zone but much higher variations anywhere else. This phenomenon is typical for registration based on landmark points or regions. Therefore, our group [4] proposed a more global approach (as opposed to the previous local regional approach) with a translation and scaling normalization on a common Best-Fit-Sphere (BFS) that produced much less and more uniform variability within the population. The next sections present an extension of these past studies. First we describe the methodology for the construction and comparison of corneal 3D atlases. Second we build a new atlas with 3876 topographies (516 topographies were used in [4]). Third, we investigate the benefit of adding rotation corrections when comparing two populations with an example comparing the left and right eyes.

II. ATLAS CONSTRUCTION

The construction of a 3D corneal shape model consists in three main steps that are presented here.

A. Step 1: Data acquisition and preprocessing

A set of corneal topographies, using any topographer (e.g. Orbscan II, Pentacam, or others) available on the market can be used. Typically, the topographer provides these datasets as two N-by-N grids (in this study N=101) where each point (x, y) has a z coordinate that indicates the elevation (height) of the (anterior or posterior) corneal surface with respect to a reference plane perpendicular to the visual axis.

B. Step 2: Spatial normalization

Spatial normalization prior to averaging is a fundamental step for the construction of any organ atlas [1][2][3]. For the

[1]Edouard Auvinet is with the Biomedical Engineering Institute - Université de Montréal and the M2S laboratory - Université de Rennes 2, auvinet@iro.umontreal.ca
[2] Jean Meunier is with the Biomedical Engineering Institute and the Department of Computer Science and Operations Research (DIRO), Université de Montréal, Montréal, QC, Canada (corresponding author). meunier@iro.umontreal.ca
[2]Isabelle Brunette, Jeb Ong, George Durr, Marina Gilca are with the Ophtalmology Research Unit, Maisonneuve-Rosemont Hospital, Montreal (QC), Canada ibrunette@videotron.ca

Fig. 1. The ORBSCAN II system.

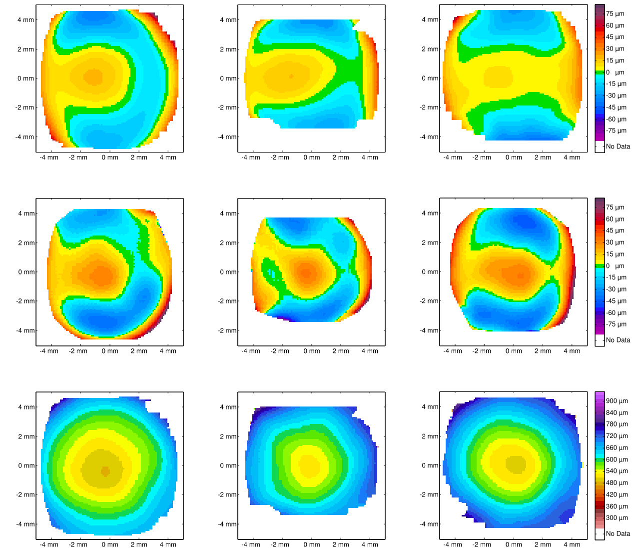


Fig. 2. Three topographies of normal subjects produced with the ORBSCAN II system. Anterior surface (top), Posterior surface (middle) and Pachymetry i.e. cornea thickness (bottom).

cornea, an overall isometric resizing to a standard size and a translation to a common reference point is computed. This means that local variations and individual features remain but differences due to the global corneal size and location in space are removed. In more details:

- BFS radii and centers for all anterior surfaces in the dataset are computed.
- A reference mean anterior BFS is defined with the average radius and center of the BFS computed in the previous step.
- Translation and isotropic scaling of all anterior and posterior surfaces in the dataset to normalize their individual anterior BFS radius and center to the same value as the reference BFS (step 2).
- Resampling of the new (transformed) anterior and posterior surface points on the original N x N (N=101) discrete grid with a bilinear interpolation. After this step, anterior and posterior surface points are normalized on a common sphere allowing averaging and comparison of shapes.

Pachymetry (cornea thickness) can also be computed between the anterior and posterior surfaces along the radius emerging from the reference sphere center. Notice that no rotation transformation is used in corneal normalization. In fact, a rotation correction is not necessary if one assumes that data acquisition is done properly with the eye always positioned with the same orientation. Furthermore our reference object for normalization is a sphere because the corneal surface is nearly spherical. Since there is no best rotation to align two spheres, rotation is useless. Alignment of individual corneas with rotation could indeed be very unstable because of their near-sphericity and variability among subjects of the same population.

C. Step 3: Shape averaging and variation assessment

After spatial normalization of the corneal volume (defined by the two surfaces), we are ready to build an atlas for the population under investigation. For each point (x, y) of the N-by-N grid of each corneal surface, the appropriate statistics are calculated. Average or median maps are usually computed for anterior and posterior surface elevations and pachymetry, with the corresponding standard deviations (SD) or percentiles. A result is returned for a point if elevation information for at least 75% of the population is available for this point.

III. ATLAS COMPARISON

Atlases also represent a powerful tool for the numerical comparison of two or more populations. The typical process for comparing two atlases consists in:

- Construction of an atlas for each population as described in section II
- Normalization of the dependant atlas on the reference (other) atlas with translation and scaling to have a common reference BFS.
- 3D rotation of the dependant atlas to minimize the difference between the two atlases. This step might be necessary to remove potential systematic differences between the two atlases due to mis-alignment with the topographer etc. Rotation correction is now possible because we are considering atlases that correspond to very stable data (mean) computed from several individual topographies.

- Computation of the elevation differences between the two atlases at each point (x, y) of the N-by-N grid for the anterior and posterior surfaces. Similarly for pachymetry.
- Computation of the appropriate statistics using the difference maps.

IV. Experimental Results

To illustrate the usefulness of corneal atlases we built a new atlas with 3876 topographies and investigated the benefit of adding rotation corrections when comparing two populations with an example comparing the left and right eyes.

A. *Atlas of right eye normal population*

A corneal atlas allows qualitative and quantitative description of the 3D corneal shape of a population. As mentioned previously this could not be done with a single topography because of the variability of these data within a population (see Fig. 2). The methodology described above was used to build a normal corneal atlas with 3876 right eye topographies of healthy subjects with no corneal diseases or previous ocular surgery aged between 5.75 and 100.06 (mean $\pm$ SD = 39.03 $\pm$ 10.26) years old taken from a dataset at the Department of Ophthalmology of the Maisonneuve-Rosemont Hospital. The topographies were obtained using the Orbscan II system. We computed the anterior BFS in a central adjustment zone of 10.0 mm in diameter. The amplitude of the isometric scaling applied to corneas for the normalization of the surfaces to the average anterior BFS varied from -10.33% to 12.22% (mean $\pm$ SD = $7.87\,\mathrm{mm} \pm 0.24$). The x, y, z translation amplitudes ranged from $-74.0\ \mu\mathrm{m}$ to $52.36\ \mu\mathrm{m}$ (mean $\pm$ SD = $-13.1\ \mu\mathrm{m} \pm 13.55$) for x, $-93.76\ \mu\mathrm{m}$ to $69.92\ \mu\mathrm{m}$ (mean $\pm$ SD = $-10.05\ \mu\mathrm{m} \pm 15.38$) for y, $-6.25\,\mathrm{mm}$ to $-4.09\,\mathrm{mm}$ (mean $\pm$ SD = $5.06\,\mathrm{mm} \pm 0.29$) for z. Fig. 3 gives a color representation of the anterior elevation, posterior elevation, and pachymetry maps for this atlas. The reference mean BFS had a radius of $7.87\,\mathrm{mm}$ and center coordinates of $(-0.013, -0.010, -5.06)$ mm. The central corneal elevation was slightly positive (yellow-orange), with a mean elevation of $7.8\ \mu\mathrm{m}$ above the anterior BFS in the $2.0\,\mathrm{mm}$ diameter central zone. The variability (SD map) was higher for the posterior surface and packymetry and lower in the central region which can be attributed in part to a lower accuracy of the Orbscan for posterior surface and peripheral measurements [5][6][7]. The average pachymetry map showed a thinner central region. The thinnest point measured $588.4\ \mu\mathrm{m}$ and was slightly displaced temporally and inferiorly with respect to the topographic center ($-0.2\,\mathrm{mm}$, $-0.2\,\mathrm{mm}$). These results are in agreement with [4] and other anatomical measurements [8].

B. *Comparison of two populations*

Atlases represent a powerful tool for the numerical comparison of two or more populations. We show here a comparison between the left and right eyes of the same subject used for atlas construction. We expect that the left eye

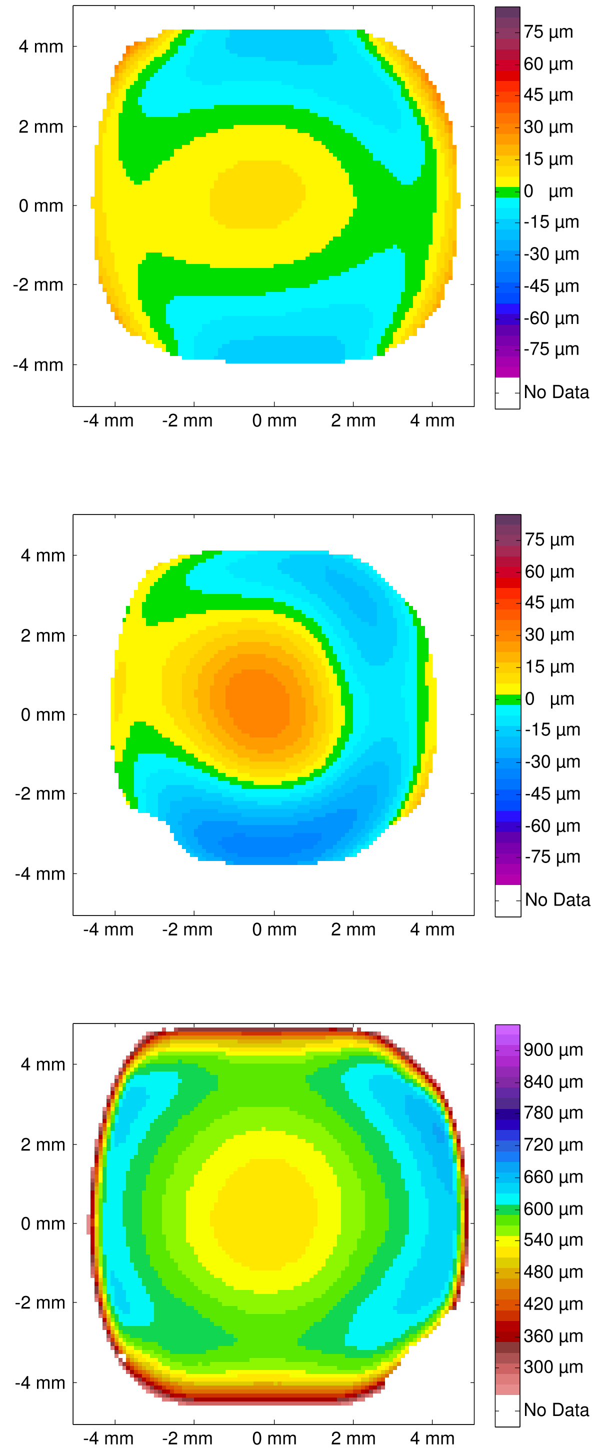
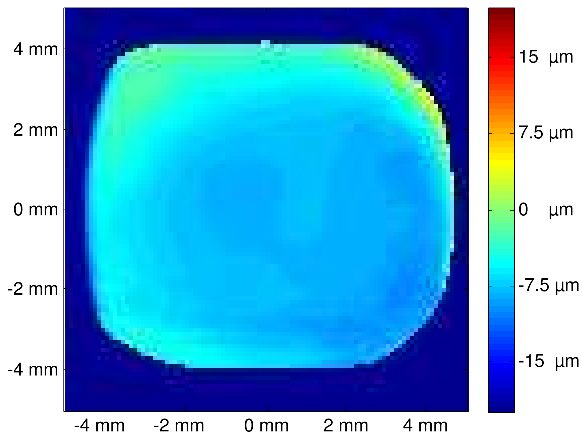
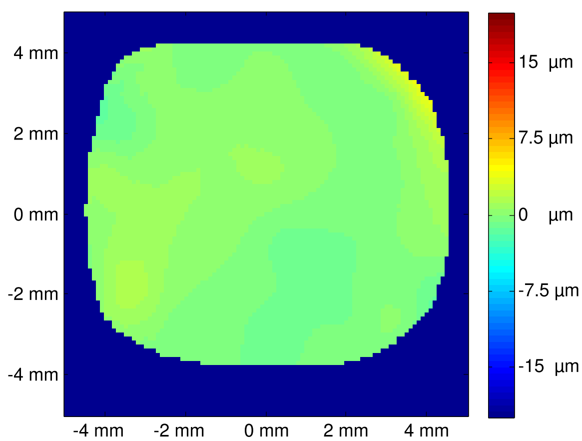


Fig. 3. Right eye atlas of a normal population. Anterior surface (top), posterior surface (middle) and pachymetry i.e. cornea thickness (bottom).



(a)



(b)

Fig. 4. Difference between atlases computed for the right and flipped left eyes of a normal population. (a) Without any normalization (b) With full normalization (including rotation correction).

shape will be identical to the right eye after a horizontal flip (mirror transformation) based on their natural symmetry. Fig. 4 shows the difference between the atlases for the right and flipped left eyes (a) without normalization, (b) with full normalization (including rotation). Clearly the differences are negligible in the latter case as expected. Differences were less than 2 microns everywhere except in the far periphery where the data are known to be less reliable [5][6][7]. These differences were within the error range of the ORBSCAN and could be considered negligible from the clinical point of view. Looking at the relatively high differences in Fig. 4a it becomes clear that normalization is a necessary step for atlas construction and comparison. The final rotation step permitted to reduce the mean difference by 3.81% of the mean difference obtained with only translation and scale registration. This was a small but significant improvement to our results.

V. DISCUSSION AND CONCLUSIONS

In this paper we have described a methodology for building 3D corneal models or atlases from topographic data and how to compare them. We have illustrated their usefulness by presenting two different examples using a large database. Other applications are possible such as screening pathologies (comparison of a subjects topography with a normal atlas), classification of corneas (by comparing with several atlases) etc. Other measurements could also be used for corneal atlas construction such as surface curvature. We have demonstrated that spatial normalization is an important step for atlas construction. By removing differences due to corneal size, location in space and rotation (for atlas comparison), quantification of morphological differences becomes feasible. However this process would be inappropriate for the analysis of absolute dimensions (e.g. absolute size or volume). The proposed scheme is not limited to the Orbscan system, any other type of instrument capable of providing corneal 3D surface points could be used to construct an atlas. We used a BFS as reference surface because this is a very simple geometrical object that can be fitted easily to elevation data which simplifies greatly the normalization process. Moreover BFS are well known and routinely used in corneal topography. However, a BFS might not be the best reference surface because a typical cornea shape is known to be slightly aspherical. In the future we intend to investigate other reference surfaces (e.g. a normal population atlas) and more sophisticated alignment algorithm for them.

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