Three-dimensional and topographic relationships between the orbital margins with reference to assessment of eyeball protrusion

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Abstract: This study investigated the topographic relationships among the eyeball and four orbital margins with the aim of identifying the correlation between orbital geometry and eyeball protrusion in Koreans. Three-dimensional (3D) volume rendering of the face was performed using serial computed-tomography images of 141 Koreans, and several landmarks on the bony orbit and the cornea were directly marked on the 3D volumes. The anterior-posterior distances from the apex of the cornea to each orbital margin and between the orbital margins were measured in both eyes. The distances from the apex of the cornea to the superior, medial, inferior, and lateral orbital margins were 5.8, 5.8, 12.0, and 17.9 mm, respectively. Differences between sides were observed in all of the orbital margins, and the distances from the apex of the cornea to the superior and inferior orbital margins were significantly greater in females than in males. The anterior-posterior distance between the superior and inferior orbital margins did not differ significantly between males (6.3 mm) and females (6.2 mm). The data obtained in this study will be useful when developing practical guidelines applicable to forensic facial reconstruction and orbitofacial surgeries.

Introduction

The topographic relationships between the eyeballs and orbital margins have an important meaning in anthropometric and clinical fields. In particular, the anterior-posterior relationship—which is the degree of eyeball protrusion in the orbit—greatly influences differences in appearance of the orbital region among individuals and racial groups. For example, East Asians generally have relatively protruding eyeballs in the orbit, while Caucasians generally have relatively deeply placed eyeballs. This difference may result from geometric differences of the bony orbit itself, such as progression or regression of the each orbital margin and general asymmetry, as well as factors related to the soft tissues [1-4]. Excessive eyeball protrusion can also represent an important clinical sign, such as thyroid-associated ophthalmopathy [5], and the degree of eyeball protrusion has been used as a criterion for the presurgical planning and postsurgical monitoring of orbitofacial surgeries.

Previous studies of the positions of the eyeballs in the orbit have mainly focused on the superior-inferior and medial-lateral relationships [6-8]. The anterior-posterior relationship has only been investigated on the basis of the lateral orbital margin [9]. Hertel's exophthalmometer was most commonly used in assessment of eyeball projection (exophthalmometry). When measuring, the deepest point of the lateral orbital margin was chosen as a landmark of the measurement because

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the soft tissue over the lateral orbital margin is very thin. However, the limitation in the accuracy has been raised since the landmark is unfixed in living body and often asymmetric between both sides [10]. In addition, the apex of cornea was believed to be tangential to a line drawn between the superior and inferior orbital margins [11-14]. Anthropometric studies of the bony orbit have focused on sex and race estimations or morphological classifications using the orbital index defined as the ratio of the height to the breadth of the orbital aperture [15-18]. Similarly, there is little literature describing the anterior-posterior relationships between the eyeballs and each of the orbital margins or among the orbital margins.

The present study investigated the topographic relationships among the eyeball and four orbital margins with the aim of determining the correlation between orbital geometry and eyeball protrusion in Koreans.

Materials and Methods

Among the patients who hospitalized with medical purposes in the Department of Plastic and Reconstructive Surgery, Konkuk University Chungju Hospital, the facial computed tomography (CT) images of 141 Korean adults (70 males and 71 females) with no thyroid disease and no surgical history of the eyes or the orbital region were used in the present study. The age range of the subjects was 20–30 years, and their mean age was 24.1 years. The mean age of male and female were 24.1 and 24.0 years, respectively. All of the subjects were informed about the procedures and subsequently consented to participate prior to the commencement of the study. This study was approved by the Ethics Committee of Konkuk University Chungju Hospital for data collection (IRB No. KUCH 2014-042) and it was performed in accordance with the principles outlined in the Declaration of Helsinki.

Serial facial CT images of the subjects were acquired under the following conditions: 120 kV, 75mA, a slice thickness of 1 mm, a voxel size of 0.395 mm, 512×512 pixels (Hispeed G, GE Healthcare, Niskayuna, NY, USA). The original CT image files were converted into the clinical image files (DICOM format) for the three-dimensional (3D) volume rendering of the skull, which was performed automatically using OnDemand3D software (Cybermed, Seoul, Korea).

The following bony landmarks were identified on 3D volumes of the skull (Fig. 1):

(1) Superior orbital margin (SOM): the uppermost point in the superior orbital margin.

(2) Inferior orbital margin (IOM): the lowest point in the inferior orbital margin (=the orbitale).

(3) Medial orbital margin (MOM): the intersection of the anterior lacrimal crest and the frontomaxillary suture (=maxillofrontale).

(4) Lateral orbital margin (LOM): the deepest point posteriorly on the lateral orbital margin.

The bony landmarks were marked directly on the 3D volume in the software. The apex of the cornea was also reconstructed after identifying the CT images in which the eyeballs and the cornea appeared the largest and the most protruding, respectively. After all of the landmarks had been marked, the 3D volume was reoriented into a standard head position in which the orbitale and the porion were placed in the same horizontal plane (Frankfurt horizontal plane). The following measurements were made on both sides and performed twice for each dimension in order to confirm the reproducibility and reliability (Fig. 2): (1) anterior-posterior distances from the apex of the cornea to the orbital margins (C-S, C-M, C-I, and C-L); (2) anterior-posterior distances among the orbital margins (L-S, L-M, L-I, and S-I); (3) difference in the degree of the protrusion between the right and left eyes.
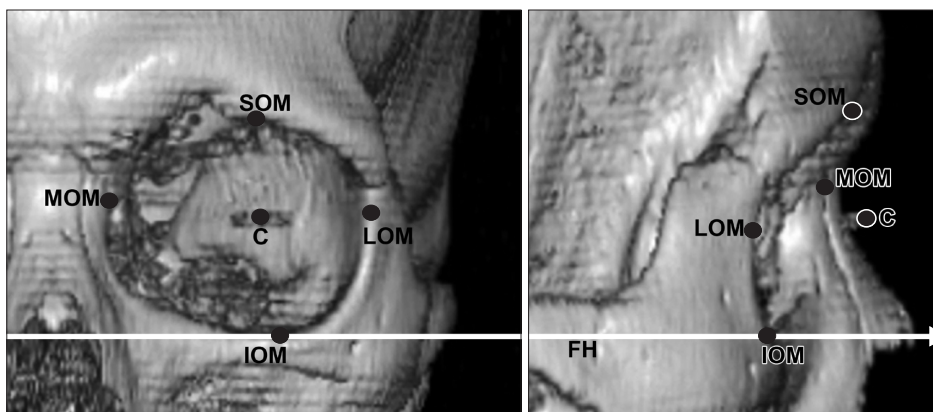

Fig. 1. Bony landmarks around the orbit. C, apex of the cornea; FH, Frankfurt horizontal plane; IOM, inferior orbital margin; LOM, lateral orbital margin; MOM, medial orbital margin; SOM, superior orbital margin.
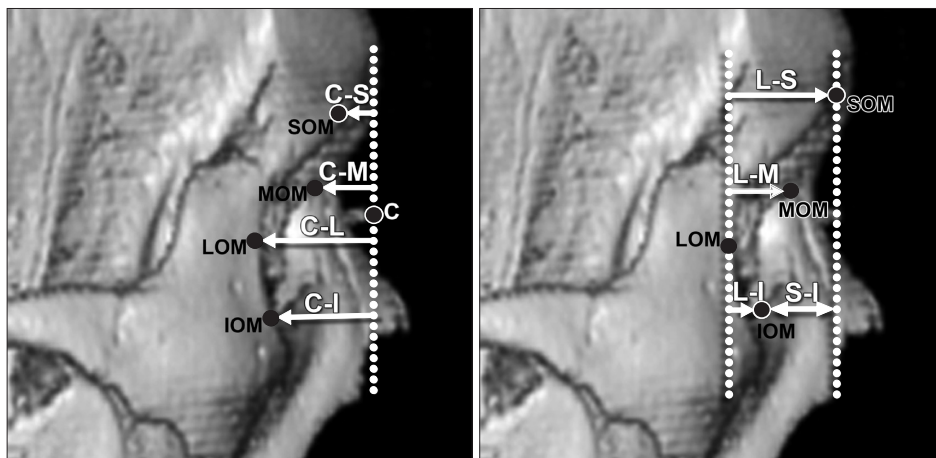
Fig. 2. The anterior-posterior distances from the apex of cornea to each orbital margin and among the orbital margins. C, apex of the cornea; C-I, cornea-IOM; C-L, cornea-LOM; C-M, cornea-MOM; C-S, cornea-SOM; IOM, inferior orbital margin; LOM, lateral orbital margin; MOM, medial orbital margin; SOM, superior orbital margin.

Table 1. Anterior-posterior distances between apex of the cornea and the orbital margins

	Side		Sex		Overall
	Right	Left	Male	Female	
Cornea-SOM (C-S)	5.3±2.1	6.3±2.0[a]	5.3±2.3	6.3±1.9[b]	5.8±2.1
Cornea-MOM (C-M)	6.0±2.1[a]	5.7±2.0	5.8±2.1	5.8±2.0	5.8±2.1
Cornea-IOM (C-I)	11.7±2.5	12.3±2.4[a]	11.6±2.6	12.4±2.3[b]	12.0±2.5
Cornea-LOM (C-L)	17.7±2.0	18.1±1.9[a]	18.0±2.1	17.9±1.8	17.9±2.0

Values are presented as mean±SD (mm). SOM, superior orbital margin; MOM, medial orbital margin; IOM, inferior orbital margin; LOM, lateral orbital margin. [a]Significant side difference. [b]Significant sexual difference.

Table 2. Anterior-posterior distances between the four orbital margins

	Side		Sex		Overall
	Right	Left	Male	Female	
LOM-SOM (L-S)	12.4±1.7[a]	11.9±1.8	12.7±1.8[b]	11.6±1.5	12.2±1.8
LOM-MOM (L-M)	11.8±2.0	12.5±2.1[a]	12.2±2.0	12.0±2.1	12.1±2.1
LOM-IOM (L-I)	6.1±1.6[a]	5.8±1.5	6.5±1.4[b]	5.4±1.6	5.9±1.6
SOM-IOM (S-I)	6.4±2.2	6.0±2.3	6.3±2.2	6.2±2.3	6.2±2.3

Values are presented as mean±SD (mm). LOM, lateral orbital margin; SOM, superior orbital margin; MOM, medial orbital margin; IOM, inferior orbital margin. [a]Significant side difference. [b]Significant sexual difference.

Table 3. The difference of protrusion between the right and left eyes

	Male	Female
Cornea-SOM (C-S)	0.9±1.5	0.9±1.4
Cornea-MOM (C-M)	0.3±1.4	0.3±1.4
Cornea-IOM (C-I)	0.4±1.2	0.4±1.0
Cornea-LOM (C-L)	0.8±1.5	0.6±1.7

Values are presented as mean±SD (mm). SOM, superior orbital margin; MOM, medial orbital margin; IOM, inferior orbital margin; LOM, lateral orbital margin.

The normality of the variables was confirmed by Kolmogorov-Smirnov test. Dependent- and independent-samples t-tests between both sides and sexes were performed using IBM SPSS Statistics version 22 (IBM Corp., Armonk, NY, USA). The cutoff for statistical significance was set at $P<0.05$.

Results

All of the measurements conformed to a normal distribution. The anterior-posterior distances from the cornea to the orbital margins differed significantly between the right and left sides. The values were larger for the left side than the right side except for C-M. C-S and C-I were significantly larger in females (6.3 mm and 12.4 mm, respectively) than in males (5.3 mm and 11.6 mm, respectively), whereas C-M and C-L did not differ with sex. In terms of overall mean values, LOM was positioned the most posteriorly on the basis of the cornea (17.9 mm), followed by IOM (12.0 mm). SOM and MOM were positioned the most anteriorly, and at the same distance (5.8 mm) (Table 1).

The anterior-posterior distances between the orbital margins were listed in Table 2. These values were calculated by subtracting between the values presented in Table 1 (e.g., C-I–C-S=S-I), and so the side and sex differences were the same as in Table 1. The anterior-posterior distance from SOM to IOM (S-I) did not differ with side or sex, and the overall mean value was 6.2 mm.

The differences in protrusion between the two eyes were less than 1 mm in all orbital margins, and they did not differ significantly with sex (Table 3). The values and patterns varied markedly between individuals.

The cornea generally protruded more than SOM, which is the most-anterior orbital margin. There were two cases in which the cornea and SOM were positioned on the same vertical line on both sides (0.7%, 2/282), and there was only one case in which the cornea was more regressed than SOM (0.4%,

1/282). These three exceptions were observed in males. There were no cases in which IOM and LOM protruded more than SOM and MOM, respectively.

Discussion

Comprehending the morphological characteristics of the orbital region requires an approach from various perspectives due to its 3D and stereoscopic structure. Several studies have examined how the position of the eyeball in the orbit varies with age and race. The degree of eyeball protrusion has been measured in several age groups from the lateral orbital margin [19] and the inferior orbital margin [20], with positive correlations between aging and eyeball protrusion commonly being reported. Previous studies comparing between racial groups found that eyeball protrusion was most prominent in African-Americans and greater in Caucasians than in Hispanics [21, 22]. However, the anthropometric and clinical significance of the anterior-posterior relationship between the eyeballs and each orbital margin has been overlooked until recently.

The appearance of the eye is determined by not only the degree of eyeball protrusion but also other factors such as the shape and size of soft tissues (e.g., eyelids and palpebral fissure) and the development of hard tissues (e.g., the brow ridge, the dorsum of the nose, and the zygomatic bone) [23]. It may therefore be considered that while the anterior-posterior relationship between the eyeballs and each orbital margin is less remarkable than that with other anatomic landmarks,

this factor plays an essential role in appearance distinctions in this region.

The anterior-posterior distance from the apex of the cornea to each orbital margin implies the position of the orbital margins relative to the cornea. A larger distance could be interpreted as an orbital margin on one side being positioned more posteriorly than that on the other side. The distances other than C-M were larger on the left side than on the right side: C-S, 6.3 vs. 5.3 mm; C-I, 12.3 vs. 11.7 mm; and C-L, 18.1 vs. 17.7 mm. In other words, SOM, IOM, and LOM of the left orbit were shifted more posteriorly than those of the right orbit, while MOM of the left orbit was shifted more anteriorly than that of the right orbit.

If these findings were caused by a difference in protrusion between the two eyes, and not by orbital asymmetry, the relationships between the various dimensions of the two sides should be consistent; however, C-M was larger on the right side. Estimating the orbital asymmetry revealed that the apertures of the left orbit were toward the posterolateral side compared to the right orbit (Fig. 3). Previous reports of asymmetry of the bony orbit have commonly described the right orbit as being larger than the left in terms of measures such as height, width, and perimeter of the orbital aperture [24-26]. A difference in the growth rates on the two sides was hypothesized, in which neural crest migration might be promoted on the right side while being delayed on the left side [27, 28]. Although it was not certain if the correlation with the findings of previous studies is due to methodological differences, the present study provides further evidence related to orbital
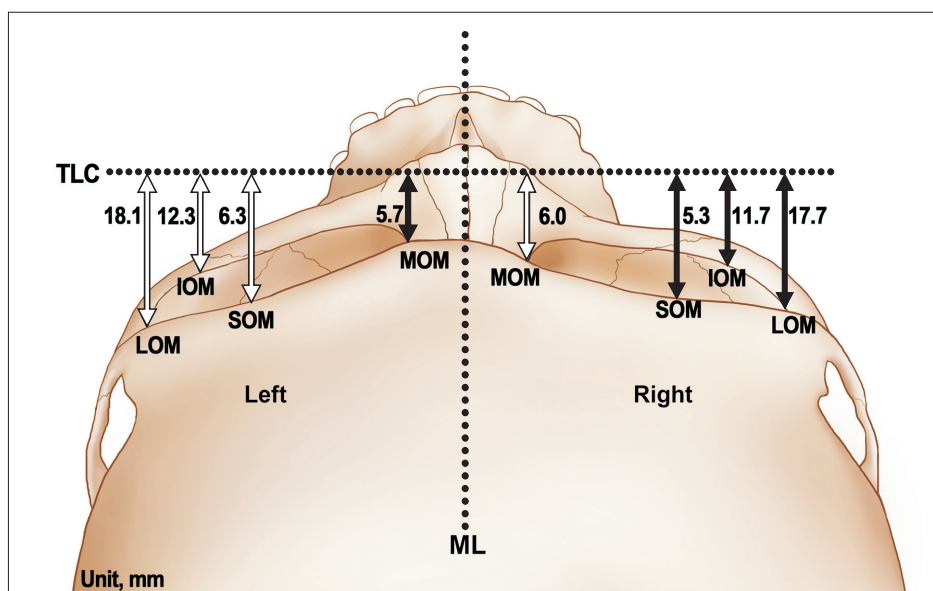

Fig. 3. Schematic superior view of the skull indicating asymmetry between the right and left orbits. The orbital margins close to and far from the apex of cornea are indicated in blak and white arrows, respectively. IOM, inferior orbital margin; LOM, lateral orbital margin; ML, midline; MOM, medial orbital margin; SOM, superior orbital margin; TLC, transverse line passing through the apex of cornea.
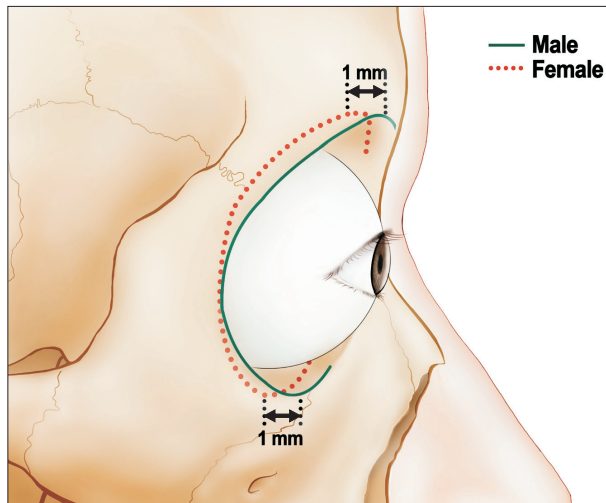
Fig. 4. Schematic illustrations of the orbital geometry and eyeball protrusion. The orbits of males (solid line) and females (dotted line) are superimposed to highlight subtle differences. Superior orbital margin and inferior orbital margin were regressed about 1 mm and the eyeballs were slightly more exposed in the orbit in females compared to males.

Table 4. Comparison with the previous studies

	Cornea-SOM (C-S)	Cornea-IOM (C-I)	Cornea-LOM (C-L)	SOM-IOM (S-I)
Present study	5.8	12.0	17.9	6.2
Goldberg et al. (1999) [31]	3.6	11.3	15.2	7.7
Richard et al. (2009) [32]	5.1	7.6	18.2	2.5
Whitaker et al. (1986) [33]	-	-	-	12.8

Values are presented as mean (mm). SOM, superior orbital margin; IOM, inferior orbital margin; LOM, lateral orbital margin.

asymmetry. It seems that orbital asymmetry has little impact on eyeball protrusion, because despite the left orbit being more slanted than the right orbit, the difference in eyeball protrusion between the two sides was less than 1 mm for all of the orbital margins, and the values and patterns varied considerably between individuals. This opinion is supported by Shah and Joshi [24] reporting that soft tissues minimize any underlying asymmetry in the hard tissues.

C-S and C-I differed significantly between males (5.3 mm and 11.6 mm, respectively) and females (6.3 mm and 12.4 mm, respectively), whereas there were no sex-related differences in C-M and C-L. The conspicuous differences in orbital geometry between males and females was attributable to the degree of SOM and IOM development, with SOM and IOM projecting about 1 mm more in males than in females. Note that S-I did not differ with sex, being 6.3 mm in males and 6.2 mm in females (Table 2). SOM and the brow ridge are generally more prominent and bulky in males than in females, and this characteristic has been used as a landmark for the sexual distinction of unidentified skulls [29]. The results of the present study seem to conflict with current knowledge. Before explaining this, consider the position of the landmark (IOM; i.e., the orbitale) used in the present study. Because the orbitale is the lowest point in the bony orbit, it is not on the median plane of the orbit, but rather inferolateral composed to the zygomatic bone. Therefore, the features of the zygomatic bone

will directly influence the position of the orbitale. S-I did not differ with sex because the zygomatic bone may be more prominent in males than in females, and so IOM will project about 1 mm more in males than in females, which will also be the case for SOM. The hypothesis of sexual dimorphism in the zygomatic bone is consistent with previous studies [30]. Consequently, the positions of the eyeballs themselves in the orbit do not differ between the sexes, but the eyeballs of males appear more regressed in the orbit than in females because the orbit is deeper due to the prominence of SOM and IOM (Fig. 4).

Comparisons with previous studies are presented in Table 4. The previous study [31] proposed reference lines for various measurements: the horizontal axis connecting the petrosal apex and the center of the eyeball, and the vertical axis defined as perpendicular to the horizontal axis and tangential to the apex of the cornea. They found that the distances from the horizontal axis to SOM, IOM, and LOM were 3.6, 11.3, and 15.2 mm, respectively; these are less than the corresponding values in the present study of 5.8, 12.0, and 17.9 mm. Similarly, a horizontal line drawn between the sella and nasion and a vertical line that was perpendicular to the horizontal line and passed through the apex of the cornea were used by Richard et al. [32] who found that the distance from the vertical line to SOM, IOM, and LOM were 5.1, 7.6, and 18.2 mm, respectively. These distances to SOM and IOM were less than those in the present study, while that to LOM was greater than in the present study.

Whitaker et al. [33] found that the anterior-posterior distance between SOM and IOM in vivo was 14.1 mm in males and 11.4 mm in females, with an overall mean of 12.8 mm; these values can be compared with those of 7.7 mm (i.e., 11.3–3.6 mm) and 2.5 mm (i.e., 7.6–5.1 mm) found by Goldberg et al. [31] and Richard et al. [32], respectively. The value of 6.2 mm found in the present study is less than those found by Whitaker et al. [33] and Goldberg et al. [31] but greater than that of Richard et al. [32]. Although it was not possible to

analyze differences between racial groups by comparing with the previous studies, due to methodological differences (e.g., research device, positions of landmarks, and ages of subjects), to the best of my knowledge the present study is the first to investigate the geometric characteristics of the orbital margins regarding eyeball protrusion in Asians. The data obtained in this study will be useful in various fields, such as for orbitofacial surgeries and forensic facial reconstruction.

Acknowledgements

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