Combined biomechanical and tomographic keratoconus staging: Adding a biomechanical parameter to the ABCD keratoconus staging system

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ABSTRACT.

Purpose: This retrospective cross-sectional study evaluated the potential of an additional biomechanical parameter ‘E’ as an addition to the tomographic ABCD ectasia/keratoconus (KC) staging.

Methods: The Corvis Biomechanical Factor (CBiF) represents the modified linear term of the Corvis Biomechanical Index (CBI) developed based on 448 KC corneas from the Homburg Keratoconus Center (HKC). The CBI range was divided into five stages (E0 to E4) to create a grading system according to the ABCD stages. Stage E0 was characterized by values smaller than the 2.5 percentile. The thresholds were created by dividing the CBiF range between the 2.5 and 97.5 percentiles into four groups of equal values (E1 to E4). The frequency distribution of ‘E’ was assessed and independently validated based on another 860 KC corneas dataset from Milano and Rio de Janeiro (MR). The relationship between ‘E’ and the ABCD staging was analysed by cross-tabulation. The specificity of ‘E’ was assessed based on healthy controls (112 samples) from both datasets (HKC/MR).

Results: ‘E’ was normally distributed with E0 = 37.3, E1 = 80.2, E2 = 155.3, E3 = 101.2, E4 = 69.7 in the KC group and 96.4% to 99.5% of the controls classified E0 in the HKC/MR dataset, respectively. Cross-tabulation revealed that ‘E’ was most comparable to posterior corneal curvature (‘B’) in both datasets, while showing a trend towards more advanced stages in comparison to anterior corneal curvature (‘A’) and thinnest corneal thickness (‘C’).

Conclusion: The novel Corvis-derived parameter ‘E’ provides a biomechanical staging for ectasia/KC potentially enhancing the ABCD staging and may detect abnormalities before tomographic changes, which requires further studies.

Key words: ABCD grading – biomechanics – Corvis Biomechanical Index – correlation – Corvis – keratoconus – tomography

Elias Flockerzi and Riccardo Vinciguerra contributed equally to this work and should be considered as equal first authors.

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Introduction

Keratoconus (KC) is a bilateral asymmetric corneal ectasia characterized by a biomechanical corneal destabilization (Ambrósio et al. 2017). This results in decreased corneal resistance to deformation, which has been attributed to a reduced corneal volume with altered proteoglycan content, reduced keratocyte (Ali et al. 2014) and nerve fibre density (Flockerzi et al. 2020), less collagen lamellae (Chan et al. 2018) and endothelial alterations (Goebeles et al. 2018).

One available tomographic KC analysis is based on the Belin/Ambrósio-enhanced ectasia display and the ABCD KC classification according to Belin and Duncan (Belin et al. 2015, 2017; Belin & Duncan 2016; Flockerzi et al. 2021a). This classification includes the stages 0 to 4 for each of the parameters: ‘A’ for anterior, ‘B’ for posterior radius of curvature (taken from a 3.0 mm optical zone centred on the thinnest corneal point), ‘C’ for thinnest corneal thickness and ‘D’ for best spectacle-corrected distance visual acuity (‘D’).

The Corneal Scheimpflug Visualization Technology (Corvis ST®, CST, Oculus, Wetzlar, Germany) measures the corneal deformation after the application of a standardized air puff
The purpose of this study was (1) to create a novel biomechanical KC staging parameter ‘E’ based on the CBiF analogous to the tomographic parameters in the ABCD KC classification and (2) to validate this parameter based on a second KC dataset derived from another location (ophthalmological departments in Milano and Rio de Janeiro (MR)).

Methods

This retrospective cross-sectional study is based upon two independent datasets of KC patients. The first dataset comprises 448 corneas of 448 KC patients and is derived from the HKC in Germany (Flockerzi et al. 2021c). The HKC is a clinical observational trial (trial number NCT03923101, U.S. National Institutes of Health, https://ClinicalTrials.gov) that was approved by the regulatory body, the local ethics committee of Saarland (Ethikkommission bei der Ärztekammer des Saarlandes, reference number 121/20). Each patient in the HKC provided written consent for the analysis of data. The second dataset, which served for validation, comprises 860 corneas of 860 KC patients from two independent centres including KC corneas from the Vincieye Clinic in Milano, Italy, and from the Rio de Janeiro Corneal Tomography and Biomechanics Study Group, Rio de Janeiro, Brazil (MR dataset). The institutional review boards in Milano and Rio de Janeiro decided that the study was exempt; however all participants provided informed consent for using their data and the study was conducted according to the tenets of the Declaration of Helsinki.

In both datasets, patients with previous operations, ocular diseases other than KC and diabetes mellitus were excluded. Keratoconus grading was analysed separately in both datasets based on the ABCD KC classification (Belin & Duncan 2016) and the eye with the more advanced KC stage was included in the KC group. KC was diagnosed (1) based on clinical slit lamp findings (corneal thinning and steepening, Vogt Striae, Fleischer ring, scar formation), (2) posterior elevation at the thinnest point ≥13 µm (based on an 8 mm reference sphere), (3) a thinnest corneal thickness <550 µm and (4) a spherical equivalent <0 (myopic)(Belin et al. 2017). Criteria (2) to (4) had to be met in KC without clinically visible signs. All KC corneas also met the criteria established in the 2015 consensus document on KC and ectatic corneal disease (Gomes et al. 2015).

Pentacam and CST measurements were repeated each time the quality score (QS) showed red. Measurements with a low-quality score, in spite of repeated attempts, were accepted for advanced disease as it is often impossible to obtain acceptable QS in these cases. The Pentacam and CST measurements were exported.

For each cornea, the CBI was transformed to its linear form, the CBI beta (CBI beta = k_0 + k_1 x A1 velocity + k_2 x DA ratio 2 mm + k_3 x ARTh + k_4 x SP-A1 + k_5 x integrated radius with k_0 = 12.693, k_1 = -60.556, k_2 = 0.639, k_3 = -0.011, k_4 = -0.0699, k_5 = 0.5407), followed by a linear transformation of the CBI beta resulting in the CBiF (CBiF = -0.24294226 x CBI beta + 6.02) as reported previously (Flockerzi et al. 2021c).

The 2.5 and 97.5 percentiles of the CBiF values were calculated and severity stages of ‘E’ (E1, E2, E3 and E4) were defined as CBiF ranges of equal partitions ranging from the 2.5 percentile to the 97.5 percentile to achieve a biomechanical staging parameter ‘E’ analogous to the tomographic parameters ‘A’, ‘B’ and ‘C’ included in the ABCD KC classification system (Belin et al. 2015). All CBiF values smaller than the 2.5 percentile were defined as stage E0. This new grading system developed based on the HKC dataset was then applied to the MR dataset.

The frequency distribution of ‘E’ was assessed within both datasets independently and thereafter compared (1) between both datasets and (2) to the respective distributions of the established tomographic ‘A’, ‘B’ and ‘C’ grading. The relationship between the biomechanical staging parameter ‘E’ and the tomographic parameters ‘A’, ‘B’ and ‘C’ was examined based on cross-tabulation.

The specificity of the biomechanical staging parameter ‘E’ in detecting normal corneas was assessed based on the data of healthy controls from the HKC and the MR departments. One eye per healthy individual was randomly chosen for analysis. The drafts of the
figures and the statistical analyses were performed using SPSS software (version 20.0; International Business Machines Corporation, Armonk, NY, USA).

**Results**

The HKC dataset included 448 KC corneas from 448 KC patients (mean age 38 ± 12.4 years) and the Milano/Rio de Janeiro (MR) dataset included 860 KC corneas from 860 KC patients (mean age 29.6 ± 6.7 years). Both datasets cover a wide spectrum of KC severity and the ratio between the right and left eyes was balanced (HKC: 47.5% left eyes, 52.5% right eyes; MR: 49.2% left, 50.8% right eyes).

In the first step, the CBiF thresholds were calculated in the HKC dataset based on the 2.5 and 97.5 percentiles to define the biomechanical KC stages E1, E2, E3 and E4. CBiF values smaller than the 2.5 percentile were defined as stage E0. An interval spacing of 0.58 was calculated in order to achieve CBiF gates with equal spacing. Table 1 shows the CBiF gates for E0, E1, E2, E3 and E4.

<table>
<thead>
<tr>
<th>Stages of 'E'</th>
<th>CBiF gates</th>
<th>Interval spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>≥5.94</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>&lt;5.94–5.36</td>
<td>0.58</td>
</tr>
<tr>
<td>2</td>
<td>&lt;5.36–4.78</td>
<td>0.58</td>
</tr>
<tr>
<td>3</td>
<td>&lt;4.78–4.20</td>
<td>0.58</td>
</tr>
<tr>
<td>4</td>
<td>&lt;4.20</td>
<td>-</td>
</tr>
</tbody>
</table>

The frequencies of these stages of 'E' were calculated in both datasets (HKC, MR). Figure 1 shows the frequency distributions of the established tomographic ABC stages and the newly developed biomechanical parameter 'E' in both KC datasets.

The 'E' stage was normally distributed in both datasets (Fig. 1a,b). Only 36 KC corneas (8.0%) in the HKC dataset and 30 (3.5%) KC corneas in the MR dataset were classified as stage E0 based on the biomechanical score 'E', respectively (Fig. 1a,b). Based on the tomographic stages, 18.5% of the HKC KC corneas were classified as A0 (MR: 21.4%), 10.3% as B0 (MR: 7.1%) and 22.5% as C0 (MR: 16.9%).

When compared with the tomographic stages 'A' and 'C', the biomechanical parameter 'E' showed a trend towards more severe stages (Fig. 1a,b) in both datasets. Although there were more cases with stage B0 than E0 in each dataset (Fig. 1a,b), the posterior

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**Table 1.** Gates for stages E0, E1, E2, E3 and E4 based on the values of the Corvis Biomechanical Factor (CBiF) in the Homburg Keratoconus Center (HKC) dataset.

![Fig. 1. ABCE KC severity distribution in this study.](image-url)

(a) HKC Distribution of "A", "B", "C", and "E"

(b) MR Distribution of "A", "B", "C" and "E"

*Fig. 1.* ABCE KC severity distribution in this study. (a) HKC dataset (n = 448 KC corneas) and (b) Milano/Rio de Janeiro (MR) dataset (n = 860 KC corneas). Blue, stage 0; brown, stage 1; green, stage 2; yellow, stage 3; red, stage 4. ‘A’, anterior radius of curvature; ‘B’, posterior radius of curvature; ‘C’, thinnest corneal thickness; ‘E’ new biomechanical grading.
Corneal surface staging ‘B’ showed an overall trend towards even more severe stages than the biomechanical staging ‘E’.

Cross-tabulation between biomechanical stages and tomographic stages

Next, a cross-tabulation between the stages of ‘E’ and the stages of ‘A’, ‘B’ and ‘C’ was performed to analyse the relationship between the biomechanical staging ‘E’ and the tomographic ABC classification. Figure 2 shows the frequency distribution for ‘E’ in dependency of each stage of ‘A’ (Fig. 2a,b), each stage of ‘B’ (Fig. 2c,d) and each stage of ‘C’ (Fig. 2e,f).

The relative frequencies of (1) similar stages of ‘E’ compared with ‘A’, ‘B’ and ‘C’, (2) more severe stages of ‘E’ compared with ‘A’, ‘B’ and ‘C’ and (3) less severe stages of ‘E’ compared with ‘A’, ‘B’ and ‘C’ were calculated to summarize the results of the cross-tabulation.

The results of this analysis are summarized in Table 2.

The biomechanical staging ‘E’ showed the highest agreement with

Fig. 2. Stages of ‘E’ in dependency of the tomographic parameters A0–A4, B0–B4 and C0–C4 in the Homburg Keratoconus Center (HKC) dataset (n = 448 KC corneas; a, c, e) and in the Milano/Rio de Janeiro (MR) dataset (n = 860 KC corneas; b, d, f).
innocuous, but rather that the detected tomographic abnormalities were so small that they did not appear in the final ABC staging (which is rounded down, e.g. A0.9 is considered A0 instead of A1). 18.5% (n = 83) of the HKC and 21.4% (n = 184) of the MR KC corneas were classified ‘A0’ despite clinically diagnosed KC (Table 3). The majority of these cases (HKC: 67% (n = 56) and MR: 88% (n = 162)) showed abnormalities within the biomechanical ‘E’ staging.

Considering ‘B’, 10.3% (HKC, n = 46) and 7.1% (MR, n = 61) were classified ‘B0’ (Table 3). Also in these cases, the majority (HKC: 56.5% (n = 26) and MR: 83.6% (n = 51)) were classified ‘E1’ or even higher.

With regards to ‘C’, 22.5% (HKC, n = 101) and 16.9% (MR, n = 145) were classified ‘C0’ and the majority of them (HKC: 67.3% (n = 68) and MR: 84.1% (n = 122)) were classified ‘E1’ or higher (Table 3).

Because the tomographic staging is based on the comprehensive analysis of ‘A’, ‘B’ and ‘C’, the biomechanical assessment is of even greater interest in cases that were normal on all three tomographic grading parameters (‘A0B0C0’): 6.3% (HKC, n = 28) and 2.1% (MR, n = 18, Table 3) were classified ‘A0B0C0’, which indicates, that they did not reveal any tomographic abnormalities in the ABC staging. Further analysis revealed, that 9 (HKC) and 12 cases (MR) showed biomechanical abnormalities and were accordingly classified ‘E1’ or higher.

Considering stage ‘E0’, biomechanical assessment provided this clinical stage in only 8.0% (HKC, n = 36) and 3.5% (MR, n = 30, Table 4). Table 4 shows the frequencies of the tomographic stages in these biomechanically innocuous cases.

This analysis confirmed that the tomographic stages ‘A’, ‘B’ and ‘C’ were also indicating stage 0 in the majority of KC corneas that were classified ‘E0’. However, some of these ‘E0’ cases were classified as stage 1 or higher in one of the three tomographic scores (Table 4).

### Sensitivity analysis

Table 3 shows the frequency distribution of ‘E’ for corneas that were classified either as ‘A0’, ‘B0’, ‘C0’ or a combination of ‘A0B0C0’. This does not mean that ‘A0B0C0’ corneas were tomographically completely normal on all three tomographic grading parameters (‘A0B0C0’), but rather that the detected tomographic abnormalities were so small that they did not appear in the ABC staging (which is rounded down, e.g. A0.9 is considered A0 instead of A1).

### Specificity analysis

The new biomechanical staging was also tested on healthy control corneas in order to analyse its specificity. For specificity analysis, 112 healthy control corneas (112 healthy patients presenting for evaluation of refractive surgery, HKC) were included with a mean age of 39.9 ± 14.9 years and a balanced distribution of left (43%) and right eyes (57%).

In addition to the HKC dataset, healthy control corneas from the MR ophthalmology departments were included as an independent validation dataset. This dataset consisted of 851 healthy corneas (851 patients) with a mean age of 34.9 ± 13.5 years and a balanced distribution of left (50.9%) and right eyes (49.1%). The frequency distribution of ‘E’ in healthy controls is shown in Fig. 3.

### Table 2. Comparison of ‘E’ stages to tomographic stages ‘A’, ‘B’ and ‘C’. Relative frequencies of ‘E’ providing similar (‘E = A/B/C’) more severe (‘E > A/B/C’) or less severe (‘E < A/B/C’) stages than the tomographic stages.

<table>
<thead>
<tr>
<th>Comparison of scores</th>
<th>Homburg frequencies (%)</th>
<th>Milano/Rio dataset (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E compared to A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E &gt; A</td>
<td>52.9</td>
<td>43.8</td>
</tr>
<tr>
<td>E &lt; A</td>
<td>28.9</td>
<td>41.4</td>
</tr>
<tr>
<td>E compared to B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E &gt; B</td>
<td>37.1</td>
<td>35.2</td>
</tr>
<tr>
<td>E &lt; B</td>
<td>10.0</td>
<td>13.4</td>
</tr>
<tr>
<td>E compared to C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E &gt; C</td>
<td>43.0</td>
<td>39.7</td>
</tr>
<tr>
<td>E &lt; C</td>
<td>48.0</td>
<td>47.8</td>
</tr>
</tbody>
</table>

### Table 3. Frequency of ‘E’ in cases that were classified ‘A0’, ‘B0’, ‘C0’ or a combination of ‘A0B0C0’.

<table>
<thead>
<tr>
<th>Frequency %</th>
<th>E0</th>
<th>E1</th>
<th>E2</th>
<th>E3</th>
<th>E4</th>
</tr>
</thead>
<tbody>
<tr>
<td>HKC (A0)</td>
<td>18.5</td>
<td>21.4</td>
<td>5.8</td>
<td>2.4</td>
<td>8.9</td>
</tr>
<tr>
<td>MR (B0)</td>
<td>10.3</td>
<td>7.1</td>
<td>4.5</td>
<td>1.2</td>
<td>4.7</td>
</tr>
<tr>
<td>HKC (C0)</td>
<td>22.5</td>
<td>16.9</td>
<td>7.4</td>
<td>2.7</td>
<td>8.7</td>
</tr>
<tr>
<td>MR (A0B0C0)</td>
<td>6.3</td>
<td>2.1</td>
<td>4.3</td>
<td>0.7</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Within the HKC dataset, 108 of 112 cases (96.4%) were classified ‘E0’ and four cases (3.6%) were classified ‘E1’ (Fig. 3). In the MR dataset, 771 of 851 cases (90.7%) were classified ‘E0’, 75 (8.8%) were classified ‘E1’ and 4 cases (0.5%) were classified ‘E2’ (Fig. 3).

In the HKC dataset, the tomographic staging revealed ‘false positive’ stages in no case for ‘A’ (MR: 1.2%), in 0.9% of cases for ‘B’ (MR: 2.8%) and 0.9% of cases for ‘C’ (MR: 5.1%).

The diagnosis and classification of KC and ectatic corneal diseases have been refined in recent years by the advent of tomographic and biomechanical analysis of the cornea by different devices. Measurement of biomechanical dynamic corneal response parameters can be performed using the CST (Vinciguerra et al. 2016, 2017; Ambrósio et al. 2017; Elham et al. 2017; Zhao et al. 2019; Langenbucher et al. 2020).

### Table 4. Frequency distribution of tomographic stages ‘A0–A4’, ‘B0–B4’ and ‘C0–C4’ in cases with the biomechanical staging ‘E0’.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Frequency</th>
<th>A0</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>A4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HKC</td>
<td>MR</td>
<td>HKC</td>
<td>MR</td>
<td>HKC</td>
<td>MR</td>
</tr>
<tr>
<td>E0</td>
<td>5.8%</td>
<td>2.4%</td>
<td>1.6%</td>
<td>0.3%</td>
<td>0.7%</td>
<td>0.7%</td>
</tr>
<tr>
<td>B0</td>
<td>HKC 4.5%</td>
<td>MR 1.2%</td>
<td>HKC 1.1%</td>
<td>B1</td>
<td>MR 0.7%</td>
<td>HKC 2.5%</td>
</tr>
<tr>
<td>C0</td>
<td>HKC 7.4%</td>
<td>MR 2.7%</td>
<td>C1</td>
<td>HKC 0.4%</td>
<td>C2</td>
<td>HKC 0.2%</td>
</tr>
</tbody>
</table>

### Discussion

The uniqueness of the ABCD KC classification lies in the additional analysis of the posterior corneal curvature, which has not been evaluated in older grading systems (e.g. Amsler-Krumeich, Topographical Keratoconus Classification (TKC) or Placido-based classifications) and which is considered to be the earliest.

The Pentacam provides tomographical measurements and generates an ABC stage according to the ABCD KC classification (Belin et al. 2015, 2017; Belin & Duncan 2016). The ABCD KC classification is the earliest.

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Fig. 3. Distribution of ‘E’ in healthy control corneas in (a) the Homburg Keratoconus Center (HKC) dataset and (b) in the Milano/Rio de Janeiro (MR) dataset.
marker for ectatic changes (Belin et al. 2017; Chan et al. 2018; Goebels et al. 2018; Flockerzi et al. 2021a) together with changes in epithelial maps (Reinstein et al. 2015; Temstet et al. 2015; Li et al. 2016; Pavlatos et al. 2020).

Biomechanical destabilization of the cornea may even precede changes on the posterior corneal curvature (Ambrósio et al. 2017; Elham et al. 2017) and, therefore, the biomechanical corneal analysis has gained an important role in the early detection not only of KC but also of other ectatic corneal diseases (Lenk et al. 2016; Yang et al. 2020). The introduction of the CBIF as a modification of the linear CBI beta provided a measure for different stages of the biomechanical destabilization of the cornea (Flockerzi et al. 2021c). The purpose of this study was to establish a link between the ABCD KC classification and corneal biomechanics by adding this biomechanical grading parameter as ‘E’ to augment the ABCD ectasia/KC staging.

The tomographic parameters A and B included in the ABCD KC classification are measured independently over a 3-mm zone centred on the thinnest corneal point, which should correspond to the location of the cone and be more representative than apical measurements. Based on those tomographic parameters, it has been demonstrated in previous studies, that they are significantly correlated with corneal biomechanical indices derived from the CST (Koh et al. 2020).

This study introduced a biomechanical grading parameter ‘E’ based on CST examination thus supplementing the tomographic ABCD KC classification. The application of this new biomechanical grading parameter ‘E’ in two independent representative KC collectives provided comparable results in terms of KC severity grading (Fig. 1a,b).

However, KC staging has to be differentiated from KC detection. The intention of the ABCDE staging is not to biomechanically diagnose KC solely based on these parameters (which is the aim of the CBI) but to further refine the severity classification. A staging system should classify the vast majority of KC cases higher than stage 0, but should indicate stage 0 in a high amount of healthy corneas.

It is therefore particularly noticeable that the biomechanical grading parameter ‘E’ shows abnormal values in some HKC cases earlier than the tomographic parameters of the ABCD KC classification. Although it has to be taken into account that this result depends on how ‘E’ was defined, a similar result was obtained in the second, independent MR dataset. Especially the lower frequency of ‘false negative’ stages of ‘E0’ compared with the tomographic stages ‘A0’, ‘B0’ and ‘C0’ in both KC datasets reveals the importance of a biomechanical assessment in early KC cases. In this study, the biomechanical staging indicated biomechanical abnormalities even in cases considered as normal in all three tomographic parameters (‘A0B0C0’) according to the ABCD KC classification. This finding is limited by the fact that an ‘A0B0C0’ staging does not imply the absence of ectatic corneal disease, because it was developed for staging instead of diagnosing KC. In these cases, the tomographic abnormalities may be so small that they are sufficient for KC diagnosis, without, however, appearing in the final ABC staging. The apparent contrast of early tomographic abnormalities but an innocuous ‘A0B0C0’ staging could thus be resolved by the addition of a conspicuous biomechanical ‘E’ staging in these cases.

This study found a trend that the most severe KC stage was set by parameter ‘B’ followed by ‘E’, ‘A’ and ‘C’ in both datasets. However, it is not possible to infer from this in principle that stages of ‘B’ are generally more advanced than stages of ‘A’ in every KC, as these are only frequency data as raised in this study. Because posterior elevation and thinnest corneal thickness were diagnostic criteria during selection of KC corneas for this study, it could be expected that they would play an important role in KC staging.

This study therefore emphasizes again the importance of posterior corneal curvature analysis but adds the importance of biomechanical analysis in the evaluation of KC. The results are also in line with the current theory that KC pathogenesis is based on a local biomechanical decompensation that leads to tomographic changes followed by further biomechanical decompensation (Roberts & Dupps 2014; Elias et al. 2019). Further, biomechanical decompensation would ultimately lead to changes on the anterior corneal surface and the appearance of the clinical changes seen in more advanced disease (Vinciguerra et al. 2016; Chan et al. 2018).

Two independent datasets of healthy control corneas were also evaluated for specificity analysis. The percentage of cases that were classified ‘E1’ or higher in healthy patients was relatively low. However, the tomographic parameters ‘A’, ‘B’ and ‘C’ showed a slightly higher specificity on these healthy cases compared with ‘E’. It will be interesting to observe, whether any of the biomechanically slightly abnormal healthy control corneas will develop signs of tomographic abnormalities in future.

A predisposition for the application and interpretation of these results is a high reliability of the CST measurements, which has been proven in recent studies: The CST measurements have been shown to be of excellent reliability in mild to moderate KC (Yang et al. 2019), in three different KC severity stages (Herber et al. 2020) and in one study assessing every KC stage according to the topographical KC classification (TKC, Flockerzi et al. 2021). Based on this high reliability of the CST measurements in all KC stages and the fact that the biomechanical staging was developed without using biomechanical information for initial diagnosis of KC, it can be assumed that the new biomechanical parameter ‘E’ introduced in this study is a robust parameter for a biomechanical KC grading.

Conclusion

This study introduced a biomechanical staging parameter ‘E’ as an addition to the tomographic ABCD ectasia/KC staging based on the separation of the CBIF into five stages (E0 to E4). The combination of topographic and biomechanical parameters may offer certain clinical advantages over either the use of either alone. Further clinical utilization of the augmented staging system is needed to ultimately determine its clinical applicability.

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