Clinical applications of the Scheimpflug principle in Ophthalmology

Aplicações clínicas do princípio de Scheimpflug na Oftalmologia

Fernando Faria-Correia, Renato Ambrósio Jr.

ABSTRACT

This article presents a review of the principles and clinical applications of the Scheimpflug principle in the anterior segment imaging. By providing a three-dimensional image of the anterior segment, this technology provides elevation and curvature data of the anterior and posterior surfaces of the cornea, pachymetric mapping, the total refractive power of the cornea and the anterior segment biometry. For the refractive surgery sub-specialty, this approach improves the ability to identify cases at risk of ectasia, as well as the planning and evaluation of the results of surgical procedures. Recently, this technology was introduced in corneal biomechanical in vivo evaluations and in femtosecond laser-assisted cataract surgery.

Keywords: Scheimpflug; Tomography; Biomechanics; Cornea; Cataract; Refractive surgery

RESUMO

Este artigo apresenta uma revisão dos princípios e das aplicações clínicas do princípio de Scheimpflug na área da imagiologia do segmento anterior. Ao disponibilizar uma imagem tridimensional do segmento anterior, esta tecnologia permite a caracterização da elevação e curvatura das superfícies anterior e posterior da córnea, o mapeamento pachimétrico, o cálculo do poder refrativo total da córnea e a biometria do segmento anterior. Na subespecialidade de cirurgia refrativa, esta abordagem melhora a capacidade de identificação de casos com risco de desenvolver ectasia, bem como de planeamento e de avaliação dos resultados dos procedimentos cirúrgicos. Recentemente, esta tecnologia foi introduzida na avaliação biomecânica in vivo da córnea e na cirurgia de catarata assistida por laser de femtossegundo.

Descritores: Scheimpflug; Tomografia; Biomecânica; Córnea; Catarata; Cirurgia refrativa

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The authors declare no conflicts of interests.

Received for publication 10/07/2015 - Accepted for publication 07/10/2015
INTRODUCTION

Advances in diagnostic capabilities have been critical to the evolution of refractive surgery, which emerged as a new subspecialty in the early 1980s. Improving imaging methods of the cornea and the anterior segment is related to the continuous need to increase the safety and effectiveness of surgical procedures. Linked to a better selection of candidates for refractive surgery, the development of diagnostic technologies dramatically favored surgical planning capabilities, including personalization of laser ablation treatment and the evaluation of results and complications of these procedures.

This knowledge also had an impact on the planning and selection of type and power of the intraocular lens to be implanted in the cataract surgery. In addition, the treatment of complex cases such as keratoconus, corneal dystrophies and other causes of irregular astigmatism also has developed due to advances in the imaging of the cornea and anterior segment.

Regarding the main obstacle to the limitations inherent in the computer technology, the technological development allowed the acquisition and analysis of images, having been key to the development of corneal topography. Stephen Klyce, PhD, is known for having developed derivative color maps of quantitative analysis of the various planes of the corneal curvature maps. The analysis of the reflected images of the Placido’s disk has been the dominant technique for the analysis of the anterior corneal surface. Alternatively, the scan photogrammetry uses a stereo triangulation technique wherein a regular pattern consisting of horizontal and vertical lines is projected onto the eye surface to reconstruct the elevation of the anterior corneal surface. Michael Belin, MD, developed the basis for calculating the elevation maps in relation to a reference surface being defined by a geometric shape (spheric, aspheric or toric ellipsoid) which best fits the actual corneal surface. However, these devices are limited to the analysis of the anterior corneal surface.

The Scheimpflug photography was used in the imaging of the anterior segment by devices EAS 1000 by Nidek (Gamagori, Japan) and SL-45 by Topcon (Tokyo, Japan). These systems have the ability to measure the dispersion of light along the optical axis, allowing the detection of changes in the transparency of the lens over time. Associated to the optical densitometry, recording these images also offer biometric measurements of the anterior segment such as the anterior chamber depth and peripheral angle measurements. However, these systems did not hold the three-dimensional reconstruction of the anterior segment.

In 1995, the optical cross-sectioning for examination of the cornea was first introduced commercially with the Orbscan [originally Orbek, Inc.] Bausch & Lomb Surgical, Salt Lake City, USA. This instrument is designed to provide topographic data (three-dimensional reconstruction), but the nomenclature regarding the CT concept was not set yet, so that it was still referred as topography.

This system introduced the slit-scanning imaging technique or the cobblestone methodology, involving the projection of 40 slits (12.50 mm height and 0.30 mm wide) with a Scheimpflug angle of 45 degrees. However, Orbscan slit images do not exhibit the same depth of field as compared to those obtained by the Scheimpflug systems (Figure 2). In its first version, the Orbscan coherence tomography, have also been recently introduced to provide dynamic measurements of the corneal deformation. Finally, imaging of the cornea and the anterior segment was also used in cataract surgery assisted by femtosecond laser.

This review focuses on the application of the Scheimpflug principle for laser refractive surgery, including its diagnostic capability and biomechanical assessment of the cornea, as well as its recent use in the planning of assisted cataract surgery by femtosecond laser.

Figure 1: Scheme of the Scheimpflug principle.
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provided information from the anterior curvature extrapolated from elevation data. In 1999, a Placido disk was integrated into the Orbscan II to obtain data directly from the anterior curvature.

The digital tomography with rotating Scheimpflug camera has been recognized as an evolution of the horizontal cross section (cobblestone methodology) in the tomographic assessment of the cornea and anterior segment. Although the capture of horizontal images does not have points in common, the system has a rotating center common to all the images, which makes the registration more precise.43,44 The Pentacam (Oculus, Wetzlar, Germany) was the first system available to perform digital tomography of the cornea and anterior segment using rotational Scheimpflug photography. This device was introduced in 1999, and introduced commercially in 2002. Pentacam, along with the rotating Scheimpflug camera, is part of a second front chamber to control the attachment and compensate the ocular alignment.

In the acquisition mode, optimal alignment is obtained with the first Purkinje reflection of the cornea using both the front chamber and the Scheimpflug one before automatically initiating the exam. A second high-resolution front camera records the size and orientation of the pupillary opening, serving as a guide for three-dimensional reconstruction. This camera also provides black-and-white measurements of the pupil size (Figure 3). The analysis of the three-dimensional Scheimpflug image provides data from the anterior and posterior surface of the cornea, anterior surface of the iris and the crystalline. As the system employs blue visible light (wavelength of 475 nm, free from ultraviolet radiation in Pentacam), that is sensitive to corneal opacities, resulting in hyperreflective images of inaccurate contour. Due to total internal reflection in the peripheral cornea, direct visualization of the anterior chamber angle is not possible. However, the extrapolation software is able to provide an estimate of the iris-corneal angle with relatively high accuracy.45 Currently, there are other business units that incorporate rotational Scheimpflug imaging technology, and in particular Galilei (Ziemer, Switzerland), TMS-5 (Tomey, Nagoya, Japan); Sirius (CSO; Florence, Italy) and Preciso (Ivis Technologies, Taranto, Italy). Table 1 presents the diagnostic capabilities of all devices with Scheimpflug imaging technology.

**Corneal tomography using the Scheimpflug principle for screening ectasia**

One of the most important applications of corneal computed tomography relates to the diagnosis of keratoconus and other ectasia diseases of the cornea.3,46-49 Pachymetry and elevation indices proved to be effective to detect keratoconus.50-52 The graphics of the spatial profile and the percentage increase in corneal thickness describe the ring pachymetry increase since the thinnest point.23,24,51 These charts are available on Pentacam and have been used successfully in the diagnosis of keratoconus.24,50,53 Pachymetry progression indices (PPI) are calculated for all semi-meridians of the cornea, such that the average of all meridians (PPI Ave) and the meridian with maximum pachymetry progression (PPI max) are reported. The “Ambrósio Relational Thickness” (ART) parameter is the ratio...
between the PPI and the thinnest point.

The “Belin-Ambrósio Enhanced Ectasia Display” (BAD; Figures 4 and 5) allows an overview of tomographic structure of the cornea by combining data from the anterior and posterior elevation, pachymetry and curvature. The BAD considers deviations from normality for different parameters, so that a zero value represents the mean of the normal population and one is the value of a standard deviation value toward the value of the disease (ectasia).³ The final ‘D’ is calculated based on the regression analysis, weighing differently the various parameters. Alternatively, Saad and Gatinel developed an efficient method of combining pachymetry and elevation data of Orbscan in discriminant functions to detect keratoconus and forme fruste keratoconus (FFKC).³⁴

Tables 2 and 3 provide the cutting values and the details of curves “receiver operating characteristic” (ROC) of the most sensitive and specific parameters for the detection of bilateral clinical keratoconus and forme fruste keratoconus (FFKC).³⁴

## Table 1
### Comparative table of instruments with Scheimpflug image

<table>
<thead>
<tr>
<th>Company</th>
<th>Pentacam</th>
<th>Galilei</th>
<th>TMS-5</th>
<th>Preciós</th>
<th>Sirius</th>
<th>Orbscan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photography</td>
<td>Oculus, Germany Rotational</td>
<td>Ziemer, Switzerland Rotational</td>
<td>Tomey, Japan Rotational</td>
<td>Ivis, Italy Rotational</td>
<td>CSO, Italy Rotational</td>
<td>Bausch&amp;Lomb, USA Horizontal cross section</td>
</tr>
</tbody>
</table>

- Placido's disk: No/Yes
- Elevation maps: Yes
- Refractive power: Yes/Yes
- map of the cornea: Yes/Yes
- Pachymetric map: Yes/Yes
- Graphic of the space profile of the thickness: No/Yes
- Cataract analysis: Yes/Yes
- Analysis of the anterior chamber: Sim

## Table 2
### Results of the curves “receiver operating characteristic” (ROC) of the parameters of Pentacam (331 normal patients vs. 242 patients with bilateral clinical keratoconus)

<table>
<thead>
<tr>
<th>Cutoff value</th>
<th>AUC</th>
<th>Standard error*</th>
<th>95% CI of AUC</th>
<th>Sensibility</th>
<th>95% CI of sensibility</th>
<th>Specificity</th>
<th>95% CI of specificity</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAD D</td>
<td>&gt;2.11</td>
<td>1</td>
<td>0.000743</td>
<td>0.993-1.000</td>
<td>99.59</td>
<td>97.7-100.0</td>
<td>100</td>
</tr>
<tr>
<td>Posterior elevation in the thinnest point (BFS)</td>
<td>&gt;12</td>
<td>0.991</td>
<td>0.00396</td>
<td>0.979-0.997</td>
<td>96.28</td>
<td>93.1-98.3</td>
<td>98.79</td>
</tr>
<tr>
<td>Posterior elevation in the thinnest point (BFTE)</td>
<td>&gt;8</td>
<td>0.994</td>
<td>0.00218</td>
<td>0.984-0.999</td>
<td>95.04</td>
<td>91.5-97.4</td>
<td>99.09</td>
</tr>
<tr>
<td>ART Avg</td>
<td>≤474</td>
<td>0.999</td>
<td>0.000663</td>
<td>0.991-1.000</td>
<td>99.59</td>
<td>97.8-100.0</td>
<td>98.19</td>
</tr>
<tr>
<td>ART Max</td>
<td>≤386</td>
<td>0.999</td>
<td>0.000674</td>
<td>0.991-1.000</td>
<td>99.17</td>
<td>97.0-99.9</td>
<td>97.28</td>
</tr>
<tr>
<td>K Max</td>
<td>&gt;47.8</td>
<td>0.978</td>
<td>0.00633</td>
<td>0.963-1.000</td>
<td>90.50</td>
<td>86.1-93.9</td>
<td>97.89</td>
</tr>
</tbody>
</table>

- a Method for standard error calculation (DeLong, 1988), listed in the software MedCalc.
- b 95% CI, confidence interval; AUC, area under the curve “receiver operating characteristic”.

## Table 3
### Results of the curves “receiver operating characteristic” (ROC) of the parameters of Pentacam (331 normal patients vs. 47 patients with forme fruste keratoconus)

<table>
<thead>
<tr>
<th>Cutoff value</th>
<th>AUC</th>
<th>Standard error</th>
<th>95% CI of AUC</th>
<th>Sensibility</th>
<th>95% CI of sensibility</th>
<th>Specificity</th>
<th>95% CI of specificity</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAD D</td>
<td>&gt;1.22</td>
<td>0.975</td>
<td>0.0121</td>
<td>0.954-0.989</td>
<td>93.62</td>
<td>82.5-98.7</td>
<td>94.56</td>
</tr>
<tr>
<td>Posterior elevation in the thinnest point (BFS)</td>
<td>&gt;5</td>
<td>0.825</td>
<td>0.0348</td>
<td>0.783-0.862</td>
<td>74.47</td>
<td>59.7-86.1</td>
<td>74.92</td>
</tr>
<tr>
<td>Posterior elevation in the thinnest point (BFTE)</td>
<td>≥1</td>
<td>0.849</td>
<td>0.0324</td>
<td>0.809-0.883</td>
<td>80.85</td>
<td>66.7-90.9</td>
<td>72.51</td>
</tr>
<tr>
<td>ART Avg</td>
<td>≤521</td>
<td>0.956</td>
<td>0.0203</td>
<td>0.930-0.974</td>
<td>91.49</td>
<td>79.6-97.6</td>
<td>93.05</td>
</tr>
<tr>
<td>ART Max</td>
<td>≤416</td>
<td>0.959</td>
<td>0.0153</td>
<td>0.934-0.977</td>
<td>85.11</td>
<td>71.7-93.8</td>
<td>93.05</td>
</tr>
<tr>
<td>K Max</td>
<td>≥45</td>
<td>0.635</td>
<td>0.043</td>
<td>0.584-0.683</td>
<td>53.19</td>
<td>38.1-67.9</td>
<td>64.05</td>
</tr>
</tbody>
</table>

- a Method for standard error calculation (DeLong, 1988), listed in the software MedCalc.
- b 95% CI, confidence interval; AUC, area under the curve “receiver operating characteristic”.

effective Pentacam parameters for identifying cornea with ectasia. Table 2 refers to a study involving an eye randomly selected from 331 normal patients and 242 patients with bilateral clinical keratoconus. Interestingly, the fact that the screening of the risk of ectasia should go beyond keratoconus detection is crucial to consider the studies that include mild or subclinical forms of ectasia.

One of the most important subgroups consists of eyes with relatively normal topography of keratoconus patients detected in the contralateral eye, being referred as FFKC. Table 3 refers to a study which included 47 corneas with FFKC, and the same control group of study of Table 2. It is critical to adjust the cutoff values to identify such mild cases or those of susceptibility to ectasia. For example, BAD-D has a cutoff value of 2.11 to detect keratoconus (99.59% sensitivity and 100% specificity; Table 2), but the best cutoff value to detect FFKC is 1.22 (93.62% sensitivity and 94.56% specificity). The optimization of the area under the ROC curve can be possible with the cutoff value, but with a minimal and tolerable loss of specificity value. For example, some parameters that are very efficient in the detection of keratoconus, such as the maximum keratometry, may not be useful in identifying cases with FFKC.

Dynamic Scheimpflug imaging to assess corneal deformation

CorVIS ST (Oculus, Wetzlar, Germany) is an NCT with a high-speed Scheimpflug camera that was launched in 2010. The coupled Scheimpflug camera covers the horizontal 8.5 mm of the cornea and captures more than 4300 images per second to monitor the response of the cornea to a collimated and calibrated puff of air. The air pulse has a fixed profile with symmetrical configuration and with maximum internal pressure of the pump of 25 kPa. During the recording time of 30 ms, 140 digital images are acquired with 576 measuring points in each. Advanced algorithms for detecting the cornea contours are applied to each image. The measurement starts with the cornea in its natural convex shape. The puff of air forces the cornea inside (ingoing phase), going through a time of aplannation (ingoing aplannation) in a concavity phase until it reaches its peak. A period of oscillation begins between the output or return phase (outgoing phase). The cornea undergoes a second moment of aplannation (outgoing aplannation) until returning to its natural shape. A possible cam motion can occur in this phase of the measurement. The time and pressure in the first and second aplannation moments and when the cornea reaches the maximum point of concavity are recorded. The intraocular pressure (IOP) is based on the deformation data. The amplitude of deformation is detected as the largest displacement of the corneal apex on the image corresponding to the moment of greatest concavity. The radius of curvature in the phase of largest concavity, the lengths and the speeds of the cornea during the apllanation phases are also recorded. The lowest value of corneal thickness is also available, and is derived from the first horizontal Scheimpflug image.

Preliminary results have shown that IOP has strong and significant influence on the corneal deformation parameters. In a study involving a model of the eye’s anterior chamber composed of hydrophilic contact lenses mounted in a sealed water chamber with adjustable pressure, three lenses with known constitutions were evaluated under different pressure levels. Each different lens showed different deformation amplitude in the pressure levels evaluated, which were greater (less rigid behavior) with lower pressure levels (P <0.001; Bonferroni post hoc test). Interestingly, when evaluated under the same internal pressure, the deformation amplitude demonstrated to be inversely related to the percentage of polymer in the lens composition. However, the thinner lens and with less polymer had an inferior deformation amplitude (more rigid behavior) at higher pressures than the thicker lenses and with more polymer, being lower of about 30% in lower than 10 microns.

Other systems available on the market, and in particular LenSx (Alcon Laboratories, Fort Worth, Texas, USA), Catalys (OptiMedica Corp., California, USA) and Victus Technolinos (Bausch & Lomb/Technolinos Perfect Vision GmbH, Germany) use optical coherence tomography (OCT) to assess the location of the intracorneal structures.

CONCLUSION

The Scheimpflug imaging technique will coexist with other technologies such as OCT and high-frequency ultrasound, but it will have an evolutive role in the area of laser refractive surgery. Continuous advances are expected to strengthen the diagnostic capabilities and surgical planning with faster generation of laser systems and high-resolution cameras also have a significant role in this evolution. Furthermore, artificial intelligence is of key importance in order to increase the safety and efficacy of customized refractive treatments.
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REFERENCES