Hertel exophthalmometry versus computed tomography and optical 3D imaging for the determination of the globe position in zygomatic fractures


Abstract. It has been the aim of the present study, to introduce the combination of computed tomography and optical 3D imaging to exophthalmometry and to compare the resulting data to the classic Hertel method. Twenty patients without orbital pathology and 12 patients were included in the study, who were subjected to a preoperative computed tomography. Optical 3D images of the facial surface were assessed and Hertel exophthalmometry was carried out to determine protrusion. In patients with zygomatic fractures the assessment of optical 3D images and Hertel values was repeated 5 days after surgery. Preoperative axial CT slices and postoperative optical contours through the globes were superimposed and the change in protrusion was determined. The protrusion values assessed either by CT, Hertel exophthalmometry or optical 3D imaging for patients without orbital pathology did not show any statistically significant differences between each other. For zygomatic fractures, Hertel exophthalmometry revealed more pronounced protrusion data in four of five cases of a postero-laterally dislocated lateral orbital rim and a higher degree of enophthalmos in cases without dislocation of the lateral orbital rim than it could be proved in the CT slices. The differences between optical measurements and CT data were minimal in patients with zygomatic fractures. The combination of computed tomography as baseline measurement and optical 3D imaging for the follow-up examinations reveal more realistic data in cases of zygomatic fractures than Hertel measurements and should be preferred.

Key words: computed tomography; exophthalmos; Hertel exophthalmometer; optical 3D imaging; zygomatic fractures.

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is comparative exophthalmos, which denotes a change in eye position over a time interval\(^2\).

Although several methods have been proposed to evaluate the globe position, the Hertel exophthalmometer is most frequently used as a simple tool in the evaluation of proptosis. It has been objected on its use that it shows a low reliability and a poor repeatability in serial measurements\(^16\). The difficulties with this method are well known. They include asymmetry of the lateral orbital rims, compression of soft tissues, parallax errors and lack of uniform technique\(^5\).

Orbit computed tomography helps to achieve more accurate values in exophthalmometry\(^3\). A major drawback is the exposure of the patient to irradiation. Stereophotogrammetric exophthalmometry has been used in experimental set-ups, but has never been applied in clinical routine\(^1\).

The use of optical 3D imaging has been recently introduced to medical sciences with high accuracy. It is used to assess optical 3D surface data \textit{in vivo} in a non-contact, non-invasive way\(^18\). It seemed reasonable to extend its use to exophthalmometry.

It has been the aim of the present study to determine the globe position in 20 adults without pathology of the orbital complex and in 12 patients suffering from zygomatic fractures by Hertel exophthalmometry, computed tomography and optical 3D imaging in order to compare the results of the different methods.

Patients and methods

The study was based on 20 patients (8 female, 12 male, 49.1 ± 17.3 years), who were examined by computed tomography of head and neck for the exclusion of different diseases. Patients were selected, when they did not show any accompanying pathology of the midface. Another 12 patients (1 female, 11 male, 38.6 ± 18.3 years), who received routine orbital computed tomography because of zygomatic fractures, were included in the study (Table 1). The study was approved by the Institutional Ethics Committee of the University of Erlangen-Nuremberg (number of approval 2221). All patients gave their informed consent to the participation in the study. Exclusion criteria were refractive errors, ocular hypotony, deviation of the nasal septum, nasal bone fractures, bilateral orbital fractures, and associated intraocular trauma. In patients with zygomatic fractures, the superficial sensory function of the infraorbital nerve was assessed by the Pointed Blunt Test, bilaterally. Moreover, these patients were examined by ophthalmologists, preoperatively and on the 5th day after surgery. Clinically detectable disorders of ocular motility and diplopia were documented. The different exophthalmometry measurements were carried out at the day of injury and 5 days postoperatively (Fig. 1).

As standard technique for the assessment of the globe position, Hertel exophthalmometry was used. With a binocular device (Exophthalmometer Hertel, Oculus Optikgeräte, Wetzlar, Germany) the distance from the corneal apex to a plane defined by the deepest point on the lateral orbital rim, on which the footplates of the device were placed, perpendicular to the frontal plane, was determined. As base value, the distance between the two footplates was documented at the first measurement and reproduced at the follow-up examinations. By this method, the apex of the cornea is viewed from sides using mirrors with superimposed millimetre rules to assess the degree of exophthalmos.

CT scans were obtained on a Somatom Volume Zoom scanner (Siemens, Erlangen, Germany) using contiguous 1 mm thick axial slices with gantry tilt of 0° parallel to the Frankfurt horizontal plane. The data were transferred to the Osiris medical imaging software Version 3.1 (Hopitaux Universitaires de Geneve, Division d'Informatique Medicales, Unite d'Imagerie Numerique, Geneva, Switzerland). Axial orbital images were selected that revealed the centre of the lens, the largest eyeball contour through the corneal apex and the deepest point of the lateral orbital rim parallel to the frontal plane with the patients looking straight forward. Parameters of absolute exophthalmometry were assessed according to Kim & Cho\(^12\).

They included the distance between the most anterior points of the lateral orbital rims of both eyes (A), the shortest distance from the corneal centre to line A \((B_{CT})\), the \(B_{CT}/A\) ratio, the distance between the most anterior points of the lateral orbital rim and the medial orbital rim \((C)\), the length of the line passing through the lens centre from the apex to line \(C\) \((D)\), the \(D/C\) ratio and the distance between the corneal apex and the posterior pole \((E)\), which is parallel to line \(B_{CT}\) and perpendicular to \(A\) (Fig. 2).

For cases with zygomatic fractures, the distance \(A\) was estimated by generating a mirror image of the sound side with nasal septum as axis of symmetry (Fig. 3).

For the data acquisition of the facial surface an optical 3D sensor (CAM\(^3\)D, 3D-shape, Erlangen, Germany, http://www.3D-shape.com/) was used (Fig. 4). The sensor is based on a modification of the phase measuring triangulation method. A sequence of phase-shifted fringe patterns of structured light is projected on the region of interest. From different directions two CCD cameras record the data. The images of the phase-shifted patterns are evaluated by means of a four-shift-algorithm to receive the three dimensional shape of

<table>
<thead>
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<tr>
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<tr>
<td></td>
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<tr>
<td>Data</td>
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Optical 3D images of the facial surface
Hertel exophthalmometry
Computed tomography
General ophthalmological examination

Optical 3D images of the facial surface
Hertel exophthalmometry

Fig. 1. Flow chart of the study of patients with zygomatic fractures.
Exophthalmometry using 3D imaging

Fig. 2. Axial computed tomography slice of a patient without pathology of the orbital region representing the exophthalmometry parameters (A=the distance between the most anterior points of the bony lateral orbital margins; B_{CT} and B_{optic}, respectively, the shortest distance from the corneal centre to line A; C=the distance between lateral and medial orbital margin; D=the length of the line passing through the centre of the lens from the corneal centre to line C; E=anterior-posterior diameter of the globe; F=corresponding contour of the facial surface assessed by optical 3D imaging).

Instead of a commonly used Ronchi ruling, sinusoidal intensity coded fringe patterns are used. The 3D sensor takes advantage of an astigmatic optical device for the projection of precise sinusoidal intensity coded fringe patterns. The optical 3D sensor was calibrated for a measurement volume of 300 x 300 x 300 mm³, adapted to the average dimensions of a human head. The required measurement time for data acquisition was 640 ms. Matted, grey, opaque soft contact lenses (Contact Color prosthetic, Contact Color, Rome, Italy, base curve 8.80, dioptr 0.00, diameter 14.50 mm) were applied to the patients, because measurements of the cornea had turned out to be difficult because of its glossy surface that produces reflections of the light source of the optical sensor with the consequence of measurement breakdown (Fig. 5). Before the contact lenses were applied to another patient, disinfection was carried out with a solution containing 4.5% glutaraldehyde, 7.4% formaldehyde and 6.4% quaternary ammonium compounds (Mucadont IS, Merz + Co, Frankfurt, Germany) for 30 min. This solution is active against HI viruses, hepatitis viruses, herpes viruses and adeno viruses. Subsequently, the contact lenses were stored in another disinfection solution (Opti-Free, Alcon Laboratories, Fort Worth, USA) for at least 6 h to inhibit bacterial growth. Before use, they were rinsed with saline solution (Eye See, Lapis Lazuli, Laren, Netherlands). The cornea was anaesthetized with a local anaesthetic (Conjunecain EDO, Dr Math Pharma, Berlin, Germany) to prevent unpleasant sensations during the application of the lenses. With the eyes looking straight forward, the optical 3D images were acquired.

From the optical 3D images the contour of the globes was assessed in a plane through the corneal apex and the deepest point of the lateral orbital rim perpendicular to the frontal plane and transferred to the Osiris medical imaging software (Fig. 6). After superimposition with corresponding computed tomography slices as parameters of exophthalmometry the shortest distance from the corneal centre found in the contour of the optical 3D image to line A (B_{optic}) was determined (Fig. 2).

Operations on the patients with zygomatic fractures were carried out within the first week after injury. General anaesthesia with oral intubation was applied. After an incision of 15 mm at the lateral eyebrow, the fracture at the frontozygomatic suture was exposed. The zygoma was reduced percutaneously by traction with a Strohmayer hook. The inferior orbital rim and the orbital floor were explored via a subciliary approach. After repositioning of the orbital content, the fragments of the orbital floor were reduced. If more than

Fig. 3. Axial computed tomography slice of a patient with a left side zygomatic fracture (A_{estimated}=estimated distance between the most anterior points of the bony lateral orbital margin by generating a mirror image of the sound side and symmetry; B_{CT reference}=the shortest distance from the corneal centre assessed by optical 3D imaging to line A_{estimated} of the sound side; B_{CT preop}=the shortest distance from the corneal centre assessed by optical 3D imaging to line A_{estimated} of the sound side; B_{CT postop}=the shortest distance from the corneal centre assessed by optical 3D imaging to line A_{estimated} of the affected side, preoperatively; B_{optic postop}=the shortest distance from the corneal centre assessed by optical 3D imaging to line A_{estimated} of the affected side, postoperatively; C=axis of symmetry; D=corresponding preoperative contour of the facial surface assessed by optical 3D imaging; E=corresponding contour of the facial surface 5 days after surgery assessed by optical 3D imaging).
0.5 cm² of the orbital floor were missing, it was reconstructed with an individually contoured, perforated sheet of polydioxanone (PDS ZX7, Ethicon, Norderstedt, Germany). By an intraoral approach, the crista zygomaticoalveolaris was exposed and reduced. For internal fixation, miniplates and monocortical screws (Champy miniplate osteosynthesis system, Martin Medizintechnik, Tuttlingen, Germany) were used at the frontozygomatic suture, the inferior orbital rim and the crista zygomaticoalveolaris.

Optical 3D imaging and Hertel exophthalmometry were repeated in the patients with orbital fractures 5 days after surgery. For the superimposition of the follow-up examinations, the healthy orbit was used as reference side and the protrusion of the reduced side (Boptic postop) was documented (Fig. 3).

Statistics
Mean values were given with standard deviations. For comparison of continuous variables in paired samples, the Wilcoxon Test was used. P-values equal to or smaller than 0.05 were considered significant. All calculations were made using SPSS Version 10 for Windows (SPSS Inc., Chicago, USA).

Results
In the group of adults without orbital pathology, the absolute exophthalmometry analysis by computed tomography revealed a mean value for the distance between the two bony lateral orbital rims (A) of 96.6 ± 7.5 mm. The shortest distance between the corneal apex and line A (protrusion, Boptic) measured 16.7 ± 4.5 mm on the right side and 16.7 ± 4.4 mm on the left side. The difference was not statistically significant (P=0.655). The distance between lateral and medial orbital rim (C) showed a mean value of 35.9 ± 3.5 mm (right) and 36.0 ± 3.4 mm (left) without statistically significant difference between the two sides (P=0.180). The length of the line passing through the lens centre from the corneal apex to line C (D) revealed a mean value of 12.2 ± 3.9 mm (right) and 12.4 ± 4.0 mm (left) (P=0.305). The anterior–posterior diameter of the globe (E) was 24.2 ± 2.0 mm on both the left and the right side (P=1.0). The BcT/A ratio and the D/C ratio showed mean values of 0.17 ± 0.04 and 0.34 ± 0.09 for both sides, respectively (P=0.655 and P=0.374, respectively). Boptic/E2 revealed a mean value of 4.6 ± 4.0 mm for the right side and 4.6 ± 3.9 mm for the left side (P=0.892) (Table 2).

Protrusion assessed by Hertel exophthalmometry showed mean values of 16.2 ± 4.8 mm for the right side and 16.6 ± 3.7 mm for the left side (P=0.525). When it was determined by optical 3D imaging and superimposition with the CT data, the corresponding values were 16.6 ± 4.4 mm for both sides (P=0.689). The protrusion values assessed either by Hertel exophthalmometry or by optical 3D imaging did not show any statistically significant differences between each other and to the data extracted from the computed tomographies (Poptic/Hertel right = 0.906, Poptic/Hertel left = 0.925, PCT/Hertel right = 0.722, PCT/Hertel left = 0.981, PCT/CToptic right = 0.572, PCT/CToptic left = 0.076).

Hertel-E/2 was 4.5 ± 3.6 mm (right) and 4.1 ± 4.6 (left), respectively (P=0.525). PCT-E/2 and Hertel-E/2, Boptic-E/2 and Hertel-E/2, and Boptic-E/2 and Boptic-E/2 did not differ significantly for both sides (PCT/Hertel right = 0.705, PCT/Hertel left = 0.981, Poptic/Hertel right = 0.906, Poptic/Hertel left = 0.925, PCT/CToptic right = 0.592, PCT/CToptic left = 0.114).

Seven zygomatic fractures affecting the left side and five affecting the right side were followed up. In eight cases the Painted Blunt Test could detect a sensitivity impairment of the innervation area of the infraorbital nerve on the fractured side. When holding the head parallel to the Frankfurt horizontal plane, four patients suffered from diplopia looking upward more than 15°.

The computed tomographies revealed an involvement of the orbital floor in the fracture site and a haematosinus in all cases. Six fractures of the orbital floor showed an entrapment of the inferior
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Because of massive swelling of the periorbital soft tissue of the affected side, the upper eyelid had to be lifted by the examiner to carry out the exophthalmometry examinations with the Hertel exophthalmometer and optical 3D imaging in five of the patients, pre- and postoperatively.

Axial CT slices were used to determine the estimated distance $A_{pre}$ preoperatively (96.8 ± 9.1 mm, Table 3). The protrusion ($B_{pre}$) of the sound sides (17.4 ± 3.1 mm) and the affected sides (18.1 ± 3.5 mm) was assessed. The statistical evaluation revealed that the values did not differ significantly ($P=0.249$). The protrusion determined from the CT images was in the same range as the protrusion ($B_{optic}$) assessed by the optical 3D data (sound side 17.6 ± 3.3 mm, affected side 18.4 ± 3.7 mm, $P_{CT/optic sound}=0.812$, $P_{CT/optic affected}=0.239$). Hertel exophthalmometry showed a protrusion of 16.5 ± 2.5 mm on the sound side and 16.9 ± 2.0 mm on the affected side. The Hertel data showed no statistically significant difference between the two sides ($P=0.427$). They also did not differ significantly from the corresponding data of CT and optical 3D imaging ($P_{CT/Hertel sound}=0.271$, $P_{optic/Hertel sound}=0.195$, $P_{CT/Hertel affected}=0.266$, $P_{optic/Hertel affected}=0.154$).

Looking at the single measurements, Hertel exophthalmometry revealed a more pronounced protrusion than the CT data in four of five cases of a posterosilaterally dislocated lateral orbital rim.

In cases without dislocation of the lateral orbital rim, the Hertel values showed an enophthalmos although a posterior shift of the globe was not apparent on the CT slices (Table 4).

Five days after surgery, optical 3D imaging showed a protrusion value of 17.6 ± 3.3 mm on the sound side that did not differ significantly from the preoperative value assessed with the same technique ($P=0.527$). The affected side revealed a protrusion value of 17.8 ± 3.3 mm. There was no statistically significant difference compared to the sound side ($P=0.075$). Hertel exophthalmometry showed protrusion values of 16.2 ± 1.9 mm for the sound side and 15.2 ± 2.4 mm for the affected side revealing an enophthalmos. However, the difference was not statistically significant for the two sides ($P=0.069$) (Table 4). The protrusion values determined by Hertel exophthalmometry and optical 3D imaging also did not differ significantly for the sound side.

Fig. 5. Patient with left side zygomatic fracture wearing contact lenses, while a fringe pattern is projected on him during acquisition of optical data.

rectus muscle. In five patients a dislocation of the lateral orbital rim of more than 2 mm in dorsolateral direction was apparent. During the operations, after the reposition of the orbital content a repair of the orbital floor had to be carried out six times with a sheet of polydioxanone (PDS ZX7, Ethicon, Norderstedt, Germany), because the remaining defect was larger than 0.5 cm².

Five days after surgery, diplopia could no longer be found in any of the patients. The eight cases of sensitivity disorders remained. However, all patients stated that the hypoesthesia was less pronounced compared to the preoperative status.
Fig. 6. Facial surface assessed by optical 3D imaging (red: facial surface assessed by left CCD camera, green: facial surface assessed by right CCD camera, black line: plane of assessment of the facial contour).

(P=0.209), while the difference between the two methods on the affected side was statistically significant (P=0.050).

Discussion

A displacement of the globe can occur because of thyroid eye disease, intraorbital tumors and craniofacial trauma. This shift can take place in any direction, depending on the location of the inciting factor. The most important measurement done clinically is the determination of the anterior–posterior axis with respect to the frontal plane of the face in order to determine the relative position of the globe within the orbital space. Exophthalmometry has been devised to assess asymmetry of protrusion between the two eyes of the same person, a comparative method to determine a change in a person’s eye position during a given interval.

Exophthalmometers like the Hertel device are placed on the facial surface. The main reason for the majority of the previous investigators of exophthalmometry to use the external orbital margin as reference point was that in this region the soft parts are very thin making it possible to place a measuring instrument almost directly on a sharp skeletal edge. These methods require an intact lateral orbital rim for fixation.
There are many orbital conditions in which the orbital rim is altered and the instruments cannot be used reliably. The results of the measurements are affected by asymmetries and other variations in the facial skeleton. It is easy to understand that the wide individual variations in the facial skeleton are probably the main cause of the great difference in values obtained already for a normal population. With regard to these factors, there is a clear limit to classic exophthalmometry already in measuring normal values of protrusion in healthy subjects. With Hertel exophthalmometry, errors in measurement can commonly occur, when the footplate is incorrectly positioned on the lateral orbital rim. Since these exophthalmometers are placed on soft tissue, the position of the reference point is dependent on the investigator. In order to reduce this practical error, it has been recommended that the same examiner performs the measurements to prevent interpersonal error. However, it seems that error is inevitable and results in a large difference in protrusion. Another factor that influences the result of exophthalmometry is that although the footplate may be placed accurately, the protrusion value may be different according to the state of the tissue and the degree of compression. In normal cases, the thickness of the soft tissue varies rather insignificantly. This is reflected by the results of the present study, where the values of absolute exophthalmometry assessed by the Hertel device for the normal population did not show relevant differences compared to the computed tomography measurements. They were in the range of previous studies. In connection with certain conditions of disease, such as a displacement of the lateral orbital rim or soft tissue oedema caused by an injury or being related to an operation, extensive changes can be found implying a source of error. In the present study, peri-orbital oedema led to an underestimation of the degree of protrusion of the injured sides, while a posterior displacement of the lateral orbital rim caused an overestimation of the protrusion, when the data were compared to computed tomography.

Contrary to Hertel exophthalmometry, the assessment of data by computed tomography and optical 3D imaging is irreplaceable of the examiner. CT has been recommended for preoperative evaluation of orbital trauma as a standard diagnostic technique. Baseline exophthalmometry data can be extracted from these images providing the bony lateral orbital rim as landmark. During the follow-up, the superimposition of CT and optical 3D imaging is adequate. The use of two-dimensional contours of the globe for relative and comparative exophthalmometry has been proposed many years before. Because of their two-dimensional nature, axial CT slices and optical contours can be easily merged to a single data set with little deviation as the data of the healthy orbit and the preoperative data of the zygomatic fractures have shown in the present study.

The assessment of data by Hertel exophthalmometry uses only one dimension and does not provide any visualization. Therefore, data superimposition with computed tomography is per se impossible.

For Hertel exophthalmometry and optical 3D imaging, without computed tomography data as reference, it is impossible to decide whether a difference in the sagittal projection of the corneal apex is the consequence of a change in size of the globe based on enlargement or shrinking is caused by a proptosis. To make sure that the axial length of the globe has remained unchanged, radiological examinations by orbital computed tomography have to be performed in order to receive reliable measurements.

In orbital trauma with dislocation of the globe, an ideal pre-event calibration is not available, but an estimation can be given by computed tomography using the intact opposite orbit as baseline in unilateral cases. In the present study, these estimated data provide information about the globe position status within the orbit of the affected side for planning the surgical strategy.

Computed tomography is accepted as tool for primary diagnostics of orbital trauma. It exposes the patient to irradiation. The use for postoperative follow-up examinations has to be confined to cases, where information on intraorbital structures is needed. If only the determination of the globe position is intended during the follow-up examinations, the application of non-ionizing optical 3D imaging is adequate.

In orbital trauma, the difference in protrusion between the two sides is more important than the absolute exophthalmometry values. To decide, whether a difference is pathological or not, the normal ranges of proptosis have to be known. A proptosis below 2 mm is not considered a relevant exophthalmos.

In the present study, the data of two patients with zygomatic fractures revealed a difference of more than 2 mm using Hertel exophthalmometry (Table 4, patients 11 and 12). CT images clearly showed a less pronounced difference. It is obvious that in these cases the use of Hertel exophthalmometry alone might have led to wrong conclusions.

Graves orbitopathy is another field, in which optical 3D imaging for exophthalmometry purposes will be of benefit for future patients. The intraoperative application of this technique allows to

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### Table 2. Exophthalmometry data (patients without pathology of the orbital region)

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<tr>
<th></th>
<th>Right</th>
<th>Left</th>
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<tbody>
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<td>A (mm)</td>
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<tr>
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<td>C (mm)</td>
<td>35.9 ± 3.5</td>
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<td>D (mm)</td>
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<td>E (mm)</td>
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<td>B&lt;sub&gt;CT/A&lt;/sub&gt; ratio</td>
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<td>D/C ratio</td>
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<td>B&lt;sub&gt;CT&lt;/sub&gt;-E2 (mm)</td>
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<td>B&lt;sub&gt;optic&lt;/sub&gt;-E2 (mm)</td>
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### Table 3. Exophthalmometry data (patients suffering from zygomatic fractures)

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<tr>
<td>C (mm)</td>
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<td>E (mm)</td>
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</tr>
<tr>
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<tr>
<td>p</td>
<td>/</td>
<td>0.249</td>
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</table>
replace the Hertel measurements for the control of the correction of exophthalmos. During the follow-up postoperative CT scans can be avoided by the use of optical 3D imaging in cases where the main interest is focused on exophthal-mometry.

Further software improvements will permit the superimposition of 3D data sets of computed tomography and optical sensors to allow for a three-dimensional evaluation of the change of globe position without loss of information. In the future, it will be possible to assess the volume change of the orbit by means of the initial CT and the optical follow-up examinations without additional exposure of the patient to irradiation.

Although optical 3D imaging requires a complex measuring device and the use of contact lenses, it is a relevant method for the improvement of relative and comparative exophthalmometry. The clinical applications of optical 3D imaging are not limited to the assessment of globe position but are multifaceted. They range from simple documentation of the facial surface to the intraoperative assessment of the changes in facial contour.12,13

The Hertel exophthalmometer will continue to serve as standard in clinical measurement of the globe position. The combination of computed tomography and 3D imaging technique will have its applications especially in complex reconstructions.

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References

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