Central Ablation Depth and Postoperative Refraction in Excimer Laser Myopic Correction Measured With Ultrasound, Scheimpflug, and Optical Coherence Pachymetry

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ABSTRACT

PURPOSE: To compare measurements of ultrasound, Scheimpflug, and optical coherence pachymetric techniques to describe ablated depth after myopic astigmatic corneal laser refractive surgery and achieved refractive correction.

METHODS: Ninety-six myopic astigmatism treatments using LASIK or LASEK in 58 patients with 3-month follow-up were retrospectively analyzed. In all cases, standard examinations, pre-/postoperative corneal topography, ocular aberrometry, and pachymetry were performed. SCHWIND Custom Ablation Manager (CAM) software and the ESIRIS laser were used for planning treatments and performing ablations. Outcomes were evaluated in terms of predictability, safety, and wavefront aberration. Pachymetry was taken before treatment (ultrasound [DGH Pachette 2], Scheimpflug [Oculus Pentacam HR], and optical coherence pachymetry [OCP] [Heidelberg-Engineering OCP]), after lifting the flap (Pachette 2, OCP), immediately after finishing ablation (Pachette 2, OCP), and at 3-month follow-up (Pachette 2, Pentacam HR).

RESULTS: At 3 months, 87 (91%) of eyes achieved 20/20 UCVA, and 89 (93%) of eyes were within ±0.50 diopters (D). Postoperative mean spherical equivalent refraction was −0.15±0.30 D. Best spectacle-corrected visual acuity improved in 30 (31%) of eyes. Differential pachymetry correlated to intended central ablation depth for all techniques: $r^2=0.60$, $P<.0001$, slope 0.81 for ultrasound; $r^2=0.75$, $P<.0001$, slope 0.97 for Scheimpflug; and $r^2=0.76$, $P<.0001$, slope 1.03 for OCP. Relative differential pachymetry correlated only marginally to achieved refractive correction for ultrasound and OCP.

CONCLUSIONS: Differential pachymetry is a metric useful for describing intended central ablation depth but not for achieved refractive correction. The rotating Scheimpflug technique offers the best estimation (closest slope to 1) and OCP offers the best correlation (closest r^2 to 1) for describing intended central ablation depth achieved. The three techniques give different measurements for ablation depth, with OCP being substantially different from ultrasound and Scheimpflug. Only borderline correlations were obtained for achieved refractive correction with ultrasound and OCP. [*J Refract Surg*. 2009;25:699-708.]

doi:10.3928/1081597X-20090707-04

Corneal laser refractive surgery reshapes the cornea based on the preoperative corneal curvature to reduce or eliminate refractive errors of the eye.[1] Currently, it is the most successful surgical treatment for the reduction of refractive error. The advantages are submicron precision of the ablation and minimal side effects.

Standard ablation profiles for the correction of myopic astigmatism are based on the removal of convex–concave tissue lenticules with spherocylindrical surfaces with the sequential delivery of laser pulses to remove the appropriate volume of corneal tissue.

Corneal thickness is a key factor at all stages of a refractive correction.[2] The volume of tissue removal determines the refractive change,[3] and corneal thickness provides structural support.[4] Ablations deeper than planned may lead to overcorrections and inadequate residual corneal thickness, which may increase the risk of postoperative keratectasia.[5]

Ultrasound is the most common method of measuring corneal thickness.[6] Newer methods based on Scheimpflug imaging[7] and optical coherence pachymetry (OCP) also allow the measurement of corneal thickness.[8] The principle of Scheimpflug imaging uses optical sectioning of the cornea with maximum depth of focus,[9] whereas OCP uses low coherence interferometry to measure corneal thickness.

In this comparison study, ultrasound, Scheimpflug, and OCP measurements were used to determine the depth of ablation and correlation to postoperative refraction for eyes

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Received: January 8, 2008; Accepted: July 29, 2008

Posted online: September 15, 2008

TABLE 1

Preoperative Data of Eyes That Underwent Excimer Laser Treatment Using the SCHWIND ESIRIS

Demographic	Mean±Standard Deviation (Range)
No. of eyes	96
No. of patients	58
Right/left eyes (n, %)	48/48, 50/50
LASIK/LASEK treatment (n, %)	78/18, 81.2/18.8
Non-custom/custom treatment (n, %)	65/31, 67.7/32.3
Optical zone diameter (mm)	6.35±0.44 (5.93 to 7.32)
MRSE (D)	−3.13±1.81 (−8.00 to −0.50)
Sphere (D)	−2.72±1.90 (−8.00 to −0.25)
Cylinder (D)	−0.82±0.90 (−2.00 to 0.00)

LASEK = laser epithelial keratomileusis, MRSE = manifest refraction spherical equivalent

that had undergone LASIK or laser epithelial keratomileusis (LASEK).

PATIENTS AND METHODS

Patients and Examinations

In this retrospective study, 96 consecutives eyes of 58 patients who underwent LASIK or LASEK at the Muscat Eye Laser Center were evaluated. The study comprised eyes that underwent surgery using the SCHWIND ESIRIS excimer laser (SCHWIND eye-tech-solutions GmbH, Kleinostheim, Germany). Table 1 shows the distribution of eyes and treatments.

Preoperative examination included uncorrected visual acuity (UCVA) and best spectacle-corrected visual acuity (BSCVA), manifest and cycloplegic refractions, corneal topography, aberrometry, pupil size, pachymetry (described below), slit-lamp microscopy, and a dilated fundus examination. Postoperative examinations were performed at 1 day, 1 week, 1 month, and 3 months. Data at preoperative and 3 months postoperative are presented.

Surgery

All surgeries were performed by one surgeon (M.C.A.) using the same LASIK or LASEK surgical techniques. The eye undergoing surgery was prepared in sterile fashion using a povidone-iodine scrub and draped to isolate the surgical field. One drop of the topical anesthetic (aurocaine; Aurolab, Aravind Eye Hospital, Madurai, India) was instilled in the eye followed by insertion of a speculum and instillation of two drops of aurocaine. Immediately before each surgery, the laser was calibrated per the manufacturer's instructions and the calibration settings were recorded.

LASIK. Prior to the keratectomy, soft intracanalicular plugs (extended duration) (Oasis Medical, Glendora, Calif) were placed in the lower puncta of both eyes. Superior-hinged LASIK flaps were created using a Carriazo-Pendular microkeratome (SCHWIND eye-tech-solutions GmbH) set for a 130-µm nominal flap thickness. The flap was reflected superiorly and the ablation was delivered to the corneal stroma using the ESIRIS excimer laser. The ESIRIS laser has a repetition rate of 200 Hz and a 0.80-mm spot size with a para-Gaussian scanning-spot profile.[10,11] Proper centration was maintained by cooperative patient fixation and a 330 Hz infrared eye tracker with a latency of 5 ms.[12] After laser ablation, the flap was reflected back in place with minimal irrigation and allowed to adhere to the stroma for 1 minute prior to discharging the patient. The postoperative topical drop regimen included one drop of Tobradex (Alcon Laboratories Inc, Ft Worth, Tex) four times daily for 1 week and Hypotears plus SDU (polyvidone 5%; Novartis Ophthalmics, Basel, Switzerland) four times a day for 3 months or Refresh Tears (sodium carboxymethylcellulose 0.5%; Allergan Inc, Irvine, Calif) four times daily for 3 months or longer.

LASEK. Prior to treatment, extended duration punctual plugs (Oasis Medical) were inserted in the lower puncta. An 8.5- or 9.5-mm optical zone marker was placed over the cornea and 17% alcohol was applied for 30 seconds. Incision of the corneal epithelium using an 8- or 9-mm trephine was performed, and the epithelial flap was lifted, folded, and placed at the corneoscleral junction. Excimer laser ablation was performed as in LASIK. After ablation, the epithelial flap was repositioned and a bandage contact lens (BIOMEDICS 55 Evolution; Cooper Vision, Hampshire, United Kingdom) was placed on the cornea. One drop of lomefloxacin 0.3% (Okacin, Novartis) and one drop of pranoprofen (Ofralar, Alcon Laboratories Inc) were instilled in the eye. Postoperatively, patients were instructed to instill topical fluorometholone (Novartis) on a tapered dose of three times daily for the first month, twice daily for the second month, and once daily for the third month. Preservative eye lubricants were prescribed three times daily for 3 months.

Treatment Planning

All treatments were planned using the SCHWIND

CAM software version 2.2 (SCHWIND eye-tech-solutions GmbH) without using a surgeon-specific nomogram. The manifest refraction was measured in each eye and compared to the objective refraction from the SCHWIND Ocular Wavefront Analyzer to ensure that the spherical equivalent difference was ≤0.50 D.[13,14] All treatments were based on the manifest refraction using CAM Aberration-Free™ treatments. Eyes with >0.50 µm of higher order aberrations preoperatively (at 6 mm) were treated using customized corneal wavefront algorithms. The average optical zone for all treatments was 6.35±0.44 mm (range: 5.93 to 7.32 mm) and ablations centered on the line of sight.[15]

Corneal Thickness Measurements

Ultrasound Pachymetry. The ultrasound pachymetry measurements were performed using the Pachette pachymeter (DGH Technology Inc, Exton, Pa). This pachymeter uses echo delay and requires the use of topical anesthetic. Corneal thickness was measured preoperatively once the patient was supine after instillation of aurocaine in the laser suite prior to flap creation, immediately after reflecting the flap for the LASIK cases, and immediately after removing epithelium for the LASEK cases, at the end of the ablation process, and at 3 months postoperatively.

Scheimpflug Pachymetry. The Pentacam camera (Oculus Optikgeräte GmbH, Wetzlar, Germany) was used to measure corneal thickness preoperatively just prior to ablation with the patient seated at the instrument and at 3 months postoperatively.

The Pentacam uses a rotating slit of light to measure the anterior segment including the cornea in cross-section. This instrument provides non-contact measurements of corneal thickness. Prior to measurement, topical lubricants or other drops were not instilled in the eye.

Optical Coherence Pachymetry. Optical coherence pachymetry has been recently introduced into clinical practice. This technique allows non-contact continuous monitoring of corneal thickness. The principle is based on low coherence interferometry. Using the Optical Coherence Pachymeter (Heidelberg Engineering GmbH, Heidelberg, Germany), the corneal thickness was monitored during the entire surgical procedure with an acquisition rate of 200 Hz. Measurements were recorded preoperatively once the patient was supine in the laser suite prior to flap creation, immediately after lifting the flap, during the ablation, and at the end of the ablation process.

All of the techniques used gave multiple values for central readings (at least one measurement). Indeed, intraoperative ultrasound readings can be variable. The selected values for ultrasound, OCP, and Scheimpflug to be recorded were decided on the basis of the median value of five measurements.

Data Analysis

Pachymetry Analysis. The difference in pachymetry measurements while the patients were supine in the laser suite prior to flap creation and immediately after flap reflection were used to calculate flap thickness.

$$FlapThickness_{US} = PreFlapPachymetry_{US} - PostFlapPachymetry_{US} \quad (1)$$

$$FlapThickness_{OCP} = PreFlapPachymetry_{OCP} - PostFlapPachymetry_{OCP} \quad (2)$$

The difference in pachymetry between measurements taken immediately after flap reflection and at the end of the laser ablation were used to calculate central ablation depth.

$$CentralAblationDepth_{US} = PostFlapPachymetry_{US} - PostAblationPachymetry_{US} \quad (3)$$

$$CentralAblationDepth_{OCP} = PostFlapPachymetry_{OCP} - PostAblationPachymetry_{OCP} \quad (4)$$

The difference in pachymetry measurements taken with the Pentacam preoperatively before flap creation and at 3 months postoperatively was used to determine central ablation depth.

$$CentralAblationDepth_{Scheimpflug} = PreoperativePachymetry_{Scheimpflug} - PostoperativePachymetry_{Scheimpflug} \quad (5)$$

The data were analyzed using *t* tests and the Bland-Altman technique, which compares two methods of measurements by plotting their differences against their mean.

Pachymetric refractive outcome was analyzed in four different manners.

1) Calculating the relative deviations in pachymetry between measured and planned central ablation depth and comparing them to the relative refractive deviations.

$$RelativeDeviationPachymetry_{US\text{-}Planned} = \frac{CentralAblationDepthUS}{CentralAblationDepth_{Planned}} - 1 \quad (6)$$

$$RelativeDeviationPachymetry_{OCP\text{-}Planned} = \frac{CentralAblationDepth_{OCP}}{CentralAblationDepth_{Planned}} - 1 \quad (7)$$

$$RelativeDeviationPachymetry_{Scheimpflug\text{-}Planned} = \frac{CentralAblationDepth_{Scheimpflug}}{CentralAblationDepth_{Planned}} - 1 \quad (8)$$

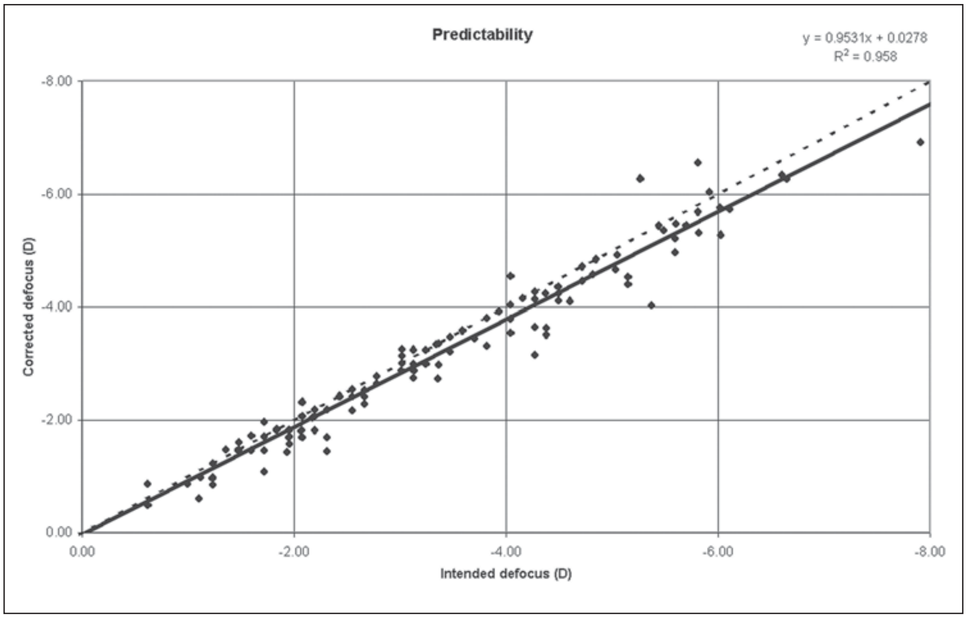

Figure 1. Predictability plot of achieved spherical equivalent correction 3 months postoperative versus attempted spherical equivalent correction of 96 eyes that underwent excimer laser treatment using the SCHWIND ESIRIS. Note the significant correlation (r^2=0.96, P<.0001) and the slope of the regression (0.95), indicating close correlation to the intended correction.

$$RelativeRefractiveDeviation = \frac{AchievedRefractiveCorrection}{AttemptedRefractiveCorrection} - 1 \quad (9)$$

2) Calculating the absolute deviations in pachymetry between measured and planned central ablation depth and comparing them to the absolute refractive deviations.

$$AbsoluteDeviationPachymetry_{US\text{-}Planned} = CentralAblationDepth_{US} - CentralAblationDepth_{Planned} \quad (10)$$

$$AbsoluteDeviationPachymetry_{OCP\text{-}Planned} = CentralAblationDepth_{OCP} - CentralAblationDepth_{Planned} \quad (11)$$

$$AbsoluteDeviationPachymetry_{Scheimpflug\text{-}Planned} = CentralAblationDepth_{Scheimpflug} - CentralAblationDepth_{Planned} \quad (12)$$

$$AbsoluteRefractiveCorrection = AchievedRefractiveCorrection - AttemptedRefractiveCorrection \quad (13)$$

3) Calculating the relative pachymetry deviations between measured and estimated central ablation depth (calculated from the linear regressions) and comparing them to the relative refractive deviations.

$$RelativeDeviationPachymetry_{US\text{-}Estimated} = CentralAblationDepth_{US}/CentralAblationDepth_{Estimated} - 1 \quad (14)$$

$$RelativeDeviationPachymetry_{OCP\text{-}Estimated} = CentralAblationDepth_{OCP}/CentralAblationDepth_{Estimated} - 1 \quad (15)$$

$$RelativeDeviationPachymetry_{Scheimpflug\text{-}Estimated} = CentralAblationDepth_{Scheimpflug}/CentralAblationDepth_{Estimated} - 1 \quad (16)$$

4) Calculating the absolute pachymetry deviations between measured and estimated central ablation depth and comparing them to the absolute refractive deviations.

$$AbsoluteDeviationPachymetry_{US\text{-}Estimated} = CentralAblationDepth_{US} - CentralAblationDepth_{Estimated} \quad (17)$$

$$AbsoluteDeviationPachymetry_{OCP\text{-}Estimated} = CentralAblationDepth_{OCP} - CentralAblationDepth_{Estimated} \quad (18)$$

$$AbsoluteDeviationPachymetry_{Scheimpflug\text{-}Estimated} = CentralAblationDepth_{Scheimpflug} - CentralAblationDepth_{Estimated} \quad (19)$$

Statistical Analysis

Preoperative and 3-month postoperative outcomes are reported. The manifest refraction, ultrasound, Scheimpflug, and OCP as well as complications were recorded and analyzed. All data were analyzed using Microsoft Excel (Microsoft Corp, Redmond, Wash). The planned central ablation depth was compared to the measured central ablation depth. Linear regression was used to determine the difference between the pachymetry measurement methods. Additionally, the correlation of central ablation depth to refractive outcome was tested. Coefficient of determination was used to determine correlation between variables under study. The *t* tests were used, with P<.05 indicating statistical significance.

RESULTS

At 3 months postoperative, all patients were available for follow-up. The average planned central ablation depth was 66±26 µm (range: 19 to 124 µm). There were no intra- or postoperative complications during the course of this study.

Refractive Outcomes

The refractive outcomes at 3 months postoperative are shown in Table 2.

Ninety-three percent of eyes (89 eyes) were within ±0.50 D of the attempted correction. Ninety-nine percent of eyes (95 eyes) were within ±1.00 D.

The achieved refractive change (Fig 1), defined as the vectorial difference in the astigmatism space between postoperative and preoperative manifest refraction, was significantly correlated with the intended refractive correction (r^2=0.96, P<.0001). The slope of regression was 0.95, indicating close correlation to the intended correction (see Fig 1). Based on the refractive power change (in terms of achieved correction), both the sphere and cylinder corrections were relatively accurate and predictable.

TABLE 2

Three-month Postoperative Refractive Data of 96 Eyes That Underwent Excimer Laser Treatment Using the SCHWIND ESIRIS

	Mean±Standard Deviation	Range
MRSE (D)	−0.15±0.30	−1.12 to +0.62
Sphere (D)	−0.03±0.30	−0.75 to +1.00
Cylinder (D)	−0.25±0.34	−0.75 to 0.00
Predictability within ±0.25 D (n, %)	79 (82.3)	
Predictability within ±0.50 D (n, %)	89 (92.7)	
Predictability within ±1.00 D (n, %)	95 (99.0)	

MRSE = manifest refraction spherical equivalent

Pachymetry Analyses

Pachymetry values pre-, intra-, and postoperatively are shown in Table 3.

Using ultrasound pachymetry as the reference measurement, good correlation of preoperative pachymetry for both Scheimpflug and OCP measurements was noted (r^2=0.84, P<.0001 for Scheimpflug; and r^2=0.83, P<.0001 for OCP). The slope of regression was 0.97 for Scheimpflug and 0.93 for OCP. Preoperative Scheimpflug pachymetry was not significantly different compared to ultrasound pachymetry (P=.22). Preoperative OCP measurements were significantly thinner than the other measurement methods (P=.0007 vs ultrasound pachymetry and P=.008 vs Scheimpflug pachymetry).

Using ultrasound pachymetry measurement as the reference measurement for flap thickness, a fair correlation of flap thickness for OCP measurements was noted (r^2=0.41, P<.0001) with a slope of 0.74; however, the difference was statistically significant (P=.0001).

TABLE 3

Corneal Pachymetry Measurements Using Three Different Techniques on Eyes That Underwent Excimer Laser Treatment Using the SCHWIND ESIRIS

		Mean±Standard Deviation (Range)		
Measurements (µm)		Ultrasound	OCP	Scheimpflug
Pachymetry				
Preoperative		543±31 (493 to 639)	532±30 (480 to 630)	539±32 (483 to 628)
After flap lift		434±30 (376 to 512)	431±31 (373 to 508)	—
After ablation		378±41 (290 to 471)	352±45 (252 to 446)	—
3-months postoperative		486±37 (416 to 536)	—	482±40 (402 to 568)
Planned flap thickness	130±0			
Flap thickness		111±19 (68 to 156)	101±16 (65 to 154)	—
Planned central ablation depth	66±26 (19 to 124)			
Central ablation depth		56±28 (12 to 136)	80±31 (15 to 155)	57±30 (13 to 130)

OCP = optical coherence pachymetry

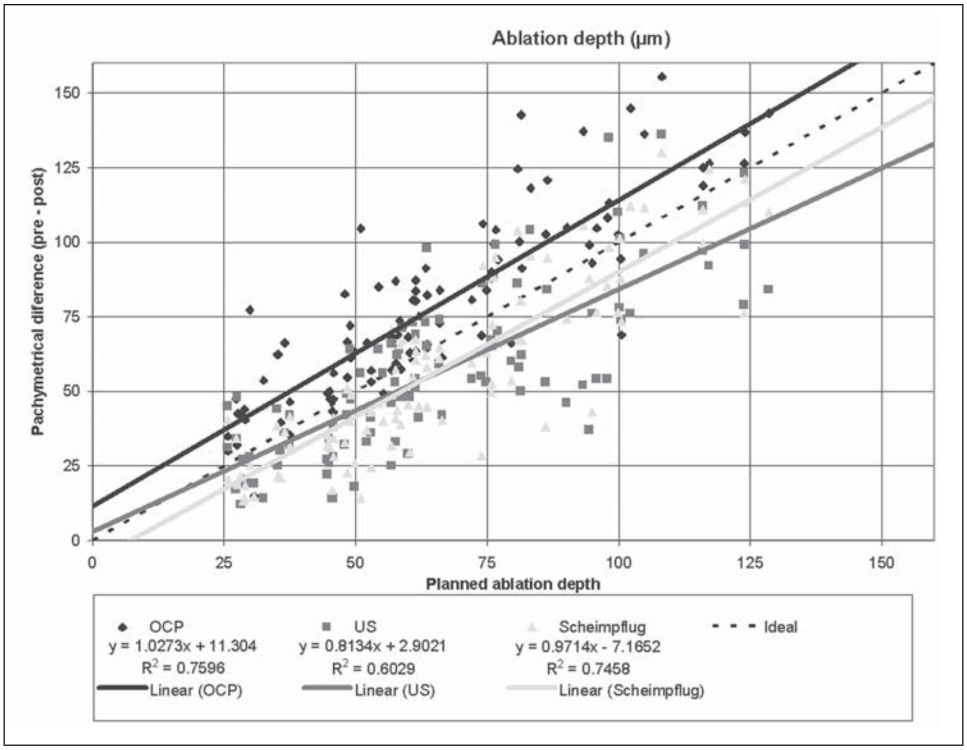

Figure 2. Correlation of central ablation depth among Scheimpflug, optical coherence pachymetry (OCP), and ultrasound pachymetry measurements versus planned central ablation depth. Planned central ablation depths as displayed by the ESIRIS are considered the reference. Note good correlation of central ablation depth for ultrasound (r^2=0.60, $P<.0001$), Scheimpflug (r^2=0.75, $P<.0001$) and OCP measurements (r^2=0.76, $P<.0001$).

Using the central ablation depth displayed on the laser screen as the reference measurement, there was good correlation of central ablation depth for ultrasound, Scheimpflug, and OCP measurements (r^2=0.60, $P<.0001$ for ultrasound; r^2=0.75, $P<.0001$ for Scheimpflug; and r^2=0.76, $P<.0001$ for OCP). The linear regression for the three measurement methods is plotted in Figure 2. The calculated depth of ablation was not significantly different from the Scheimpflug and ultrasound measurements (P=.47). Optical coherence pachymetry estimations were significantly deeper than ultrasound pachymetry ($P<.0001$) and Scheimpflug pachymetry ($P<.0001$). All three methods of central ablation depth estimation were significantly different from planned central ablation depth. Correlation to the calculated central ablation depth was highest for OCP, with a mean overestimation of +13 μm (P=.0008) followed by ultrasound with a mean underestimation of −10 μm (P=.008) and Scheimpflug with a mean estimation of −9 μm (P=.01).

Bland-Altman Plots

Bland-Altman plots show the agreement among the three measurement methods for preoperative pachymetry (Fig 3A), flap thickness (Fig 3B), and central ablation depth (Fig 3C).

For preoperative pachymetry compared to ultrasound, a bias was shown by both the OCP and Scheimpflug methods, with the Scheimpflug showing better agreement (see Fig 3A). The linear regressions of OCP compared to ultrasound or Scheimpflug show a tendency for the mean difference to rise with increasing preoperative corneal thickness magnitude (see Fig 3A).

Good agreement was noted for flap thickness measurements between ultrasound and OCP with the limits of agreement (±1.96 standard deviations) ranging from +38 μm (+32%) to −19 μm (−16%) (see Fig 3B).

A tendency for the mean difference to increase with increasing central ablation depth occurred when comparing the ultrasound or Scheimpflug techniques to OCP (see Fig 3C). There was an opposite trend when comparing ultrasound to Scheimpflug pachymetry measurements (see Fig 3C).

Pachymetric Refractive Outcome

No correlation for any of the pachymetry methods was observed when calculating the relative deviation in pachymetry between measured and planned central ablation depth and comparing them to the relative refractive deviations.

Calculating the absolute deviations in pachymetry between measured and planned central ablation depth and comparing them to the absolute refractive deviations showed no correlation for the Scheimpflug measurements (P=.62), a borderline correlation for OCP (P=.06), and a significant correlation for ultrasound measurements (P=.03) (Fig 4).

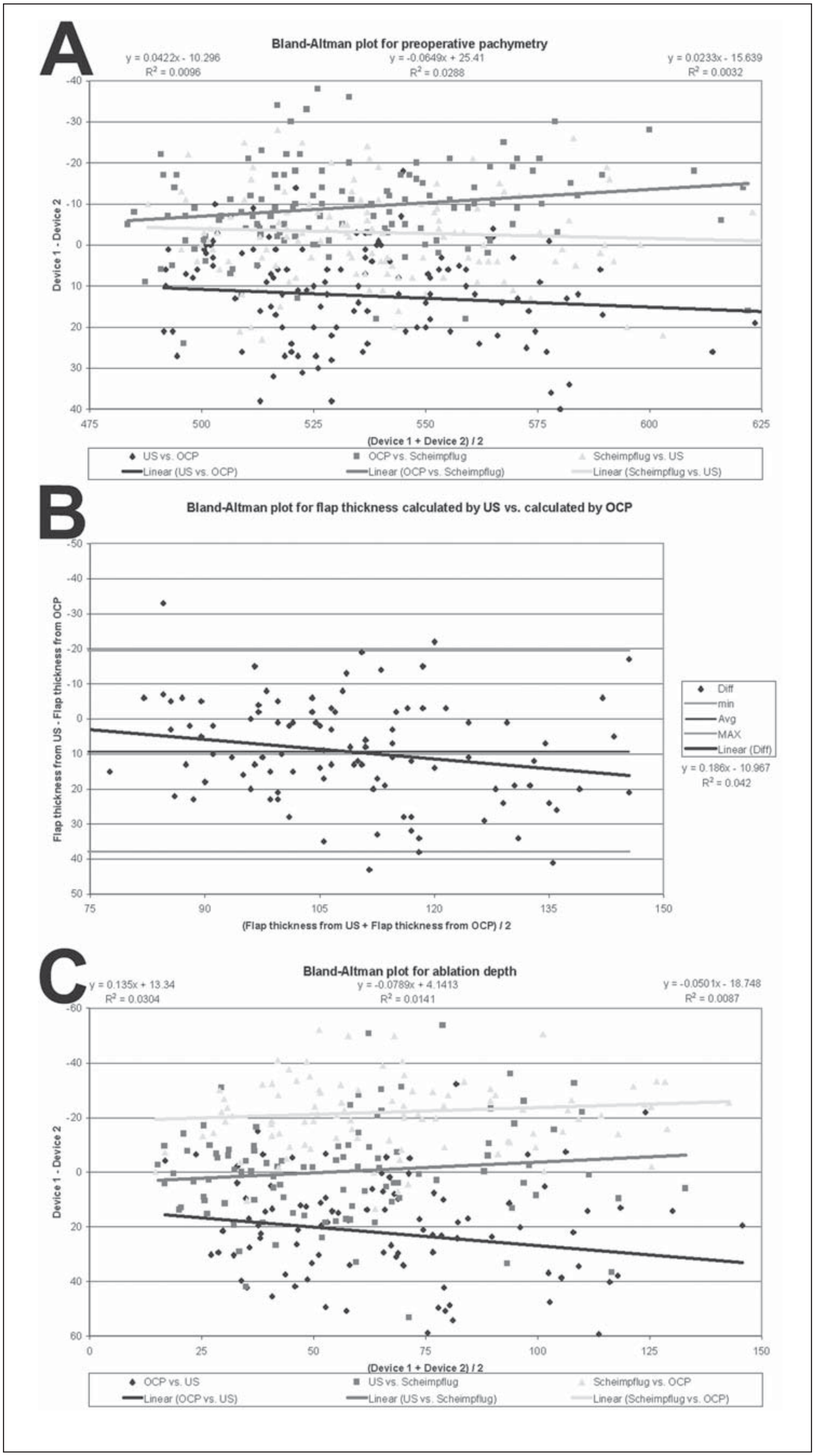

Figure 3. Bland-Altman plots (difference between corresponding measurements obtained from two different devices versus their respective semi-sums) for the three measurement methods. **A)** Corneal thickness. For preoperative pachymetry compared to ultrasound, a bias was shown by both the optical coherence pachymetry (OCP) and Scheimpflug methods, with the Scheimpflug showing better agreement. The linear regressions of OCP compared to ultrasound or Scheimpflug show a tendency for the mean difference to rise with increasing preoperative corneal thickness magnitude. **B)** Flap thickness. Good agreement was noted for flap thickness measurements between ultrasound and OCP with the limits of agreement (±1.96 standard deviation) ranging from +38 μm (+32%) to −19 μm (−16%). **C)** Central ablation depth. A tendency for the mean difference to increase with increasing central ablation depth occurred when comparing the ultrasound or Scheimpflug techniques to OCP. There was an opposite trend when comparing ultrasound to Scheimpflug pachymetry measurements.

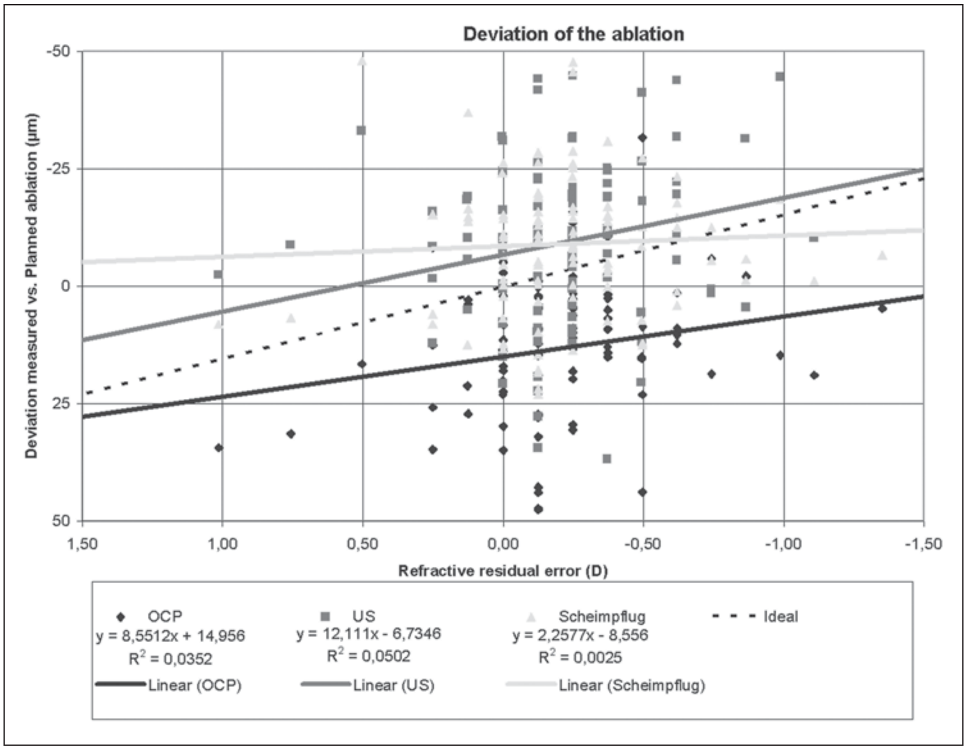

Figure 4. Measured central ablation depth minus planned central ablation depth as displayed by the ESIRIS versus residual manifest refraction spherical equivalent 3 months postoperative for Scheimpflug, optical coherence pachymetry (OCP), and ultrasound pachymetry measurements. Calculated absolute deviations in pachymetry between measured and planned central ablation depth compared to the absolute refractive deviations showed no correlation for the Scheimpflug measurements (P=.62), a borderline correlation for OCP (P=.06), and a significant correlation for ultrasound measurements (P=.03).

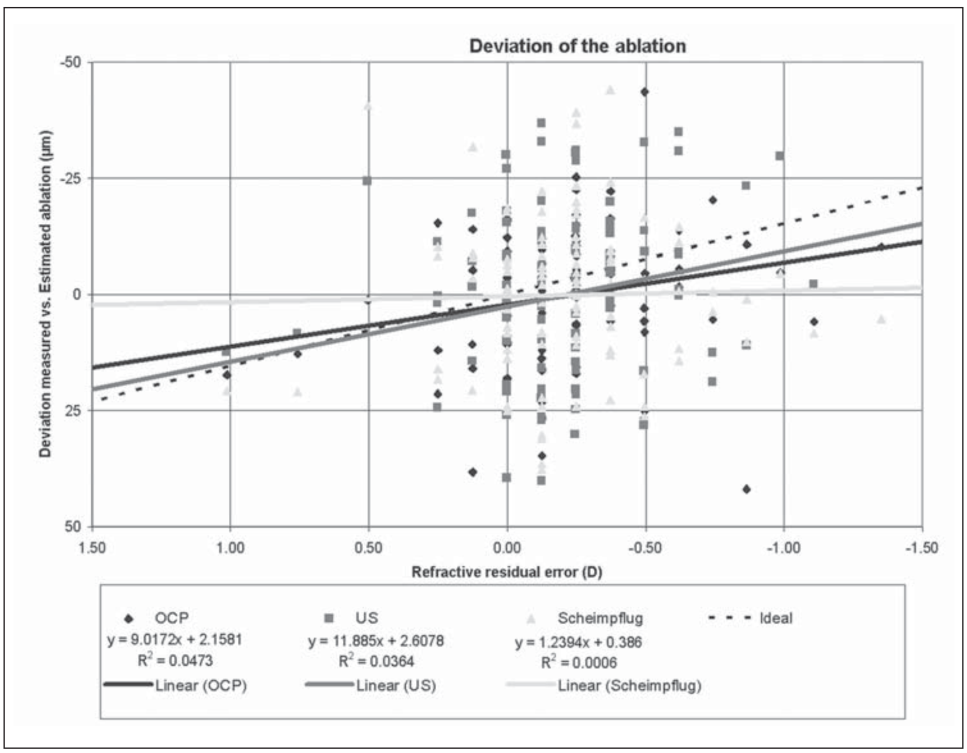

Figure 5. Measured central ablation depth minus estimated central ablation depth versus residual manifest refraction spherical equivalent at 3 months postoperatively for Scheimpflug, optical coherence pachymetry (OCP), and ultrasound pachymetry measurements. Calculated absolute pachymetry deviations between measured and estimated central ablation depth compared to the absolute refractive deviations showed no correlation for the Scheimpflug method (P=.80), a borderline correlation for ultrasound measurements (P=.06), and significant correlation for OCP (P=.03).

Calculating the relative pachymetry deviations between measured central and estimated central ablation depth and comparing them to the relative refractive deviations showed no correlation for any of the three measurement methods.

Calculating the absolute pachymetry deviations between measured and estimated central ablation depth and comparing them to the absolute refractive deviations showed no correlation for the Scheimpflug method (P=.80), a borderline correlation for ultrasound measurements (P=.06), and significant correlation for OCP (P=.03) (Fig 5).

DISCUSSION

In the present study, the ESIRIS system was predictable and accurate. For example, 93% (89 eyes) had a postoperative refraction within ±0.50 D of the attempted correction (Table 2). Additionally, the attempted versus achieved refractive change was closely correlated (r^2=0.95, P<.0001) (see Fig 1).

Preoperative corneal thickness measurements correlated well for the three measurement techniques investigated in this study. However, OCP measurements were statistically significantly thinner compared to both Scheimpflug and ultrasound measurements (P=.0007 vs ultrasound pachymetry and P=.008 vs Scheimpflug pachymetry). A similar correlation was reported by Borderie[16] between OCP and ultrasound pachymetry.

A fair correlation was observed between ultrasound and OCP flap thickness measurements (r^2=0.40, P<.0001, slope of 0.74); however, OCP measured statistically significantly thinner flaps (P=.0001). Thinner flap measurements using OCP compared to ultrasound pachymetry have been reported previously.[17] Based on these outcomes, flap thickness measurements with OCP must be interpreted with caution.

A highly significant correlation between the corneal pachymetry changes and the planned central ablation depth were found for all three techniques (see Fig 2). The best correlation was with OCP (r^2=0.76, P<.0001), followed by Scheimpflug (r^2=0.75, P<.0001) and ultrasound (r^2=0.60, P<.0001). Scheimpflug provided the best estimation, slightly underestimating the central ablation depth, followed by OCP, which slightly overestimated the central ablation depth and ultrasound, which underestimated the central ablation depth.

Optical coherence pachymetry estimations were statistically significantly deeper than the other two methods (P<.0001 vs ultrasound pachymetry and P<.0001 vs Scheimpflug pachymetry), whereas Scheimpflug and ultrasonic estimates were not statistically different (P=.47).

The difference in theoretical versus measured ablation depth may be partially explained by the variability in corneal epithelial remodeling, which differs from patient to patient. For example, theoretical calculations cannot account for this variability in corneal response whereas measurements directly incorporate this variability. This likely explains the lack of one-to-one correlation between theoretical and measured central ablation depth for all three techniques. Additionally, changes in corneal thickness between pre- and intraoperative measurements using the same instrument have been documented previously.[17,18]

Optical coherence pachymetry generated higher central ablation depth values compared to the other methods. This was likely due to corneal dehydration during laser ablation.[17] Unlike the other two methods, OCP provides continuous measurement during the laser ablation and likely incorporates the effect of dehydration, which increases the volume of tissue ablated. This dehydration effect may be transient and can only be detected with continuous monitoring. Similar to the present study, Wirbelauer et al[19,20] also reported good correlation with central ablation depth. However, they found the ablations were 29% deeper than planned,[19,20] compared to the 11% deviation observed in our study. Continuous monitoring of the effect of corneal dehydration ensures that adequate residual stromal bed thickness remains after ablation to maintain the biomechanical integrity of the cornea.

The Scheimpflug unit is not portable and ultrasound pachymetry would require numerous interruptions of the laser ablation to perform measurements. Akin to biometry, contact ultrasound pachymetry may also cause compression of the cornea. This compression may cause a divot that could accumulate fluid, masking the ablation and leading to central islands. Artifactually, higher pachymetry measurements may be caused due to fluid coupling on the ultrasound probe. The advantage of non-contact measurements is that they reduce the chance of infection. From the practical perspective, OCP is the best method of the three to continually monitor corneal thickness.

None of the three measurement techniques were effective at predicting the achieved refractive outcome. This is because the major determinant of corneal refractive power is corneal curvature not the change in corneal thickness. Changes from the ideal relationship between central ablation depth and residual refractive error would possibly allow the detection of residual refractive error during excimer laser treatment. From this perspective the ultrasound and OCP techniques gave encouraging results with borderline correlations. The advantage of these methods over Scheimpflug is the direct measurement during or immediately after the ablation.

Based on the work of Wirbelauer et al[19,20] and the present study, OCP allowed the clinical evaluation of intraoperative ablation parameters during refractive surgery. Further studies are required to assess the active control of excimer laser ablation from continuous monitoring, which may improve laser algorithms and nomograms. Intraoperative OCP could be an important safety feature to monitor the flap thickness during LASIK and residual stromal thickness during refractive surgery. The individual central ablation depth and possible dehydration effects are also monitored continuously. Thus, OCP, if further developed and standardized, could contribute to improved safety standards during refractive surgery.

The present study demonstrated that changes in pachymetry can be effectively used for monitoring and analyzing corneal laser refractive surgeries, helping circumvent biomechanical weakening of the cornea. The three pachymetric techniques compared herein (OCP, ultrasound, and Scheimpflug) were repeatable and accurate and can be used to assess pre- and postoperative corneal thickness. However, the Scheimpflug technique cannot be used to assess intraoperatively (eg, flap thickness and central ablation depth during treatment).

The advantage of Scheimpflug imaging over the other two methods is that it provides pachymetry measurements over the entire cornea and is not limited to central or local pachymetry. Currently, the limitation of OCP is that it can only acquire single points of measurements. From the outcomes of the present study, central ablation depth can be assessed from the difference in corneal thickness, but changes in refraction are dependent on the modification of the corneal curvature. Therefore, OCP is valuable to intraoperatively assess central corneal changes, flap thickness, and residual stromal thickness.

AUTHOR CONTRIBUTIONS

Study concept and design (M.C.A., S.A.M.); data collection (M.C.A., C.V.); interpretation and analysis of data (M.C.A., S.A.M.); drafting of the manuscript (M.C.A., S.A.M.); critical revision of the manuscript (M.C.A., C.V.)

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