INVITED REVIEW

Title:

Optical Coherence Tomography and Scleral Contact Lenses: Clinical and Research Applications

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ABSTRACT

Anterior segment optical coherence tomography (OCT) provides a wealth of opportunities for modern contact lens practice. OCT imaging has numerous clinical and research applications related to the tear film, cornea, conjunctiva, sclera and ocular adnexae, in addition to soft, rigid, and hybrid contact lenses. This review summarises the potential use of OCT imaging in modern scleral contact lens practice including initial lens selection, assessing the scleral contact lens fit with respect to the cornea and sclera, and accurately quantifying the ocular response to lens wear. Recent advances in the understanding of anterior segment metrics including scleral thickness, curvature, astigmatism, and the anatomy of the corneoscleral limbal junction are also discussed.

Over the past decade, scleral contact lens prescribing has increased globally, largely due to advances in contact lens manufacturing and ophthalmic instrumentation, in particular optical coherence tomography (OCT).¹ The benefits of scleral contact lenses have been described in detail elsewhere, including; the correction of high ametropia, neutralising irregular anterior corneal optics, corneal protection, and therapeutic rehabilitation of the ocular surface.^{2–6} These unique clinical applications have remained largely unchanged since glass haptic shells and lenses were first described in the late 19th century.^{7,8} In modern contact lens practice, scleral lenses can also delay the need for corneal transplantation in keratoconus⁹ and in a number of clinical scenarios are considered the contact lens correction of choice, particularly for complex ocular shapes.

Scleral contact lenses have been successfully fitted for over 130 years using a diagnostic fitting approach that primarily relied upon impression moulding to estimate scleral topography, and practitioner observation and intuition interpreting sodium fluorescein patterns, or alterations in the conjunctival and superficial scleral vasculature (haptic compression). Nowadays, in addition to manufacturer fitting algorithms, practitioners routinely utilise corneoscleral topographical data and OCT imaging as part of an empirical fitting approach (which complements diagnostic lens fitting), to determine the most appropriate initial trial lens, objectively assess the central and peripheral lens fit, and customise lens design. This review examines the role of OCT imaging in modern scleral contact lens practice and potential research applications.

ANTERIOR SEGMENT ANATOMY AND MORPHOMETRY

A comprehensive understanding of the biometrics of the anterior segment is integral to both scleral contact lens design and fitting. Since the introduction of anterior segment OCT imaging in 1994,¹⁰ the understanding of corneal, conjunctival and scleral morphometry has continued to grow, and in recent

years commercial OCT systems have become valuable clinical tools which inform initial scleral lens selection and aid the fitting assessment or troubleshooting. Since larger diameter scleral lenses are designed to vault the corneal apex and limbus, align with the underlying sclera within the haptic landing zone and induce minimal adverse changes to the superficial tissue layers (the conjunctiva, Tenon's capsule, and the episclera), high resolution cross-sectional images of a scleral lens in situ provides valuable clinical information in addition to slit lamp biomicroscopy.

Corneal thickness

The high-resolution of current anterior segment OCT instruments ($\sim 5\text{-}10\text{ }\mu\text{m}$ in corneal tissue)¹¹ enables reliable visualisation, segmentation and quantification of each corneal layer, particularly with the use of B-scan averaging to improve image quality (Figure 1). Customised anterior segment OCT imaging systems can also provide an axial resolution of close to $1\text{ }\mu\text{m}$ in corneal tissue.¹² Most commercial OCT instruments have automated corneal thickness segmentation incorporated within the manufacturer provided software, which can assist with the identification and monitoring of corneal ectasia¹³ and scleral lens induced corneal oedema.^{14,15}

Scleral thickness

OCT imaging also allows high-resolution repeatable, non-invasive measurement of scleral tissue in-vivo. Previous estimates of scleral thickness were limited in various ways by the measurement technique used. For example, tissue section in cadavers is affected by structural changes in post-mortem eyes,¹⁶ ultrasound biomicroscopy requires tissue contact, and magnetic resonance imaging is costly and inaccessible to eye care practitioners.¹⁷ In addition, ultrasound and magnetic resonance imaging (MRI) have relatively low resolution compared to OCT ($\sim 150\text{-}250\text{ }\mu\text{m}$ for MRI^{18,19}).

A number of recent studies using OCT imaging have advanced the understanding of the morphometry of the sclera, and the overlying episclera,

Tenon's capsule and conjunctiva. The thickness of the anterior sclera varies with measurement meridian (thickest nasally, then temporally, superiorly and inferiorly partly due to the location of extraocular muscle insertion points)^{20,21} and with measurement location, being thickest closer to the scleral spur and thinning posteriorly towards the equator.^{20,22} Sex-related differences (thicker in males²²) and an age-related thickening of the anterior sclera have also been reported.^{21,22} Scleral thickening from childhood to adulthood appears to be associated with an increase in scleral proteoglycans,²³ and age-related structural changes later in life vary with ethnicity.^{24,25} Similar to the conjunctiva, the sclera undergoes diurnal variation being thickest immediately after waking in the morning and thinnest around midday.²⁶

OCT imaging can also be used to quantify conjunctival and scleral compression during and following scleral lens wear. Tissue compression will vary with each lens design (primarily influenced by the tangent and curvature of the landing zone, the total lens diameter, and potentially the insertion technique). Tissue compression may affect tear exchange, comfort during lens wear, the extent of conjunctival staining following lens removal, and potentially intraocular pressure given the location of the haptic zone to the canal of Schlemm (Figure 2).²⁷⁻²⁹

Scleral curvature

A number of methods have been used to determine the curvature of the anterior sclera including measurements obtained from cadaver eyes and ocular impressions,^{30,31} and more recently Scheimpflug imaging and anterior eye profilometry.³² In order to obtain the profile of the ocular surface for scleral contact lens fitting, as early as 1888,³⁰ an impression of the eye was used to make a mould from which a lens could be cast that provided a realistic estimate of both corneal and scleral height and curvature along all meridians. However, impression moulding was variable and dependent upon examiner skill. Lenses manufactured from impression moulding still required numerous modifications to adjust the final fit to minimise conjunctival blanching or increase corneal clearance, due to the somewhat unpredictable nature of lens settling on eye.

Since the introduction of OCT imaging, and the widespread use of preformed scleral lenses, impression moulding is relatively uncommon, and is typically reserved for complex ocular shapes (for example, extreme ocular deformation and post-surgical eyes). A consistent finding from all studies examining the curvature of the anterior sclera using OCT imaging is that the sclera is significantly steeper temporally compared to nasally (Figure 3), with substantially less variation between the nasal, superior, and inferior quadrants.^{33–38} The curvature of the sclera varies with the ocular meridian examined, the distance from the limbus, subject age, the method used to fit a curve to the OCT image, and correction for instrument related optical distortion (Table 1).

The corneoscleral limbal junction

The shape of the limbal junction, where the cornea meets the sclera, informs contact lens design and influences the lens fit and potentially patient comfort during scleral lens wear. Prior to the advent of OCT imaging, Meier³⁹ devised a qualitative scale of corneoscleral shapes based on clinical observation, with a gradual tangential limbal profile most commonly observed (a relatively flat straight transition from cornea to sclera). While the overall radius of curvature of the sclera is significantly flatter than the curvature of the peripheral cornea, the sclera often continues as a tangential extension of the peripheral cornea in the peri-limbal region (~80% of eyes exhibit an anterior scleral angle within $\pm 2.5^\circ$ of the peripheral corneal angle³⁴) (Figure 4). The angle of the corneoscleral junction varies with the ocular meridian, being sharpest (a less obtuse angle) nasally and flattest (closest to a tangent) superiorly (Figure 5).^{33,34,40} The greatest asymmetry in the corneoscleral junction angle is typically observed along the horizontal meridian,^{33,34,40} which may contribute to excessive limbal clearance or lens stand-off temporally and reduced limbal clearance nasally.⁴¹ The corneoscleral junction angle also steepens slightly with age³⁴ and varies with ethnicity (a more pronounced angle in Caucasians compared to Asians).⁴² While OCT imaging has allowed the reliable

quantification of this angle, it remains difficult to measure accurately due to the ambiguity of the exact location that the cornea transitions to the sclera.

The corneal and scleral angle

A number of studies have used OCT imaging to measure the corneal and scleral angles; the angle between the anterior corneal or scleral surface and a horizontal chord orthogonal to the corneal normal (typically a 10-12 mm chord for the cornea and 15-20 mm chord for the sclera) (Figure 4). The scleral angle is of particular importance with respect to landing zone alignment. Scleral angles at a 15 mm chord (a common landing zone for miniscleral lens designs) can range from ~30-47 degrees,^{43,44} however, the vast majority lie between 37-41 degrees, in both normal and keratoconic eyes.⁴⁴⁻⁴⁶ Consequently scleral lens manufacturers often specify adjustable tangent angles rather than peripheral curvatures to modify limbal clearance and the alignment of the landing zone.

Meridional differences in the scleral angle increase with increasing distance from the limbus,⁴⁰ most notably a nasal-temporal asymmetry, particularly for chord lengths greater than 15 mm (for example, an increase in the maximum meridional difference of ~2° at 15 mm up to ~7° at 20 mm).⁴⁴ Therefore, rotationally symmetric lens designs with a proximal landing zone edge of ~15 mm or less should provide an adequate fit for most eyes, however, a toric or quadrant specific haptic zone may be required for larger diameter lenses to achieve a comfortable, stable fit with appropriate landing zone alignment.

Scleral sagittal height or elevation

An additional metric intrinsically linked to the scleral angle and radius of curvature is the scleral sagittal height or elevation, defined as the distance from the tangent to the corneal apex to a parallel reference chord (Figure 4). Sagittal height data obtained from OCT imaging can be used to describe meridional differences in scleral elevation (often referred to as scleral astigmatism or toricity) at the approximate landing zone position, since a limited number of

imaging devices can reliably quantify curvature measurements beyond the mid-peripheral cornea.^{32,47} Scleral toricity has been defined as the greatest difference in scleral sagittal height between two perpendicular meridians (for a specified chord),⁴⁰ and increases with increasing distance from the limbus (~100 μm at 15 mm chord to 400 μm at a 20 mm chord).^{40,43} This further emphasises that for smaller diameter scleral lenses (with a proximal landing zone edge of 15 mm or less) a rotationally symmetric lens design may be acceptable, however, larger scleral lenses may require customised haptic designs to ensure lens stability with minimal decentration and lens flexure (particularly for thinner lenses and scleral toricity $\geq 200 \mu\text{m}$).⁴⁸

Scleral sagittal depth data is particularly useful for initial scleral lens selection (after factoring in additional depth to allow for adequate corneal clearance and lens settling), since measures of corneal radius of curvature only partially correlate with the back optic zone radius of the optimal scleral lens.⁴⁹ Similarly, corneal astigmatism is of little use in initial lens selection because there is a weak relationship between corneal and scleral astigmatism for both magnitude and orientation.^{37,40,48,50} Gemoules⁵¹ first described the potential of OCT imaging to aid scleral lens fitting and design in 2008. He used sagittal height data across a 16 mm chord to determine the curvature of the peripheral cornea and anterior sclera to design customised semi-scleral lenses for patients who could not achieve an acceptable fit with a rotationally symmetric trial lenses due to excessive corneal clearance, post-lens tear layer bubble formation. While scleral contact lens fitting is possible through diagnostic lens assessment and interpreting scleral compression patterns, OCT imaging facilitates empirical fitting, aids troubleshooting, and can minimise the number of lenses required to obtain an acceptable fit.

ASSESSING THE FIT OF SCLERAL CONTACT LENSES

Scleral lenses sink into the relatively thin superficial tissues overlying the sclera (conjunctiva, Tenon's capsule, and episclera) during wear,²⁰ which results in tissue compression beneath the lens haptic or landing zone, and a reduction in

the thickness of the post-lens tear layer both centrally and at the limbus. The magnitude of corneal clearance has important optical and physiological implications during scleral contact lens wear.

Central corneal clearance

While OCT imaging provides the most accurate and repeatable estimate of corneal vault, it should be noted that raw (uncorrected) corneal clearance data obtained from an OCT image is not the true level of corneal clearance, since anterior segment thickness measurements are affected when imaging through a contact lens due to optical distortion.⁵²⁻⁵⁵ OCT instruments also assume a uniform ocular refractive index for thickness calculations, which is altered when a lens is worn during imaging. For example, using an assumed corneal refractive index that is lower than the actual refractive index of a rigid contact lens and the cornea in combination would result in a slight underestimation in thickness values.⁵⁶

Optimal central corneal clearance

Large diameter scleral lenses were originally fitted with generous apical clearance (500-1500 μm),⁵⁷ however, this approach was later revised to minimise central corneal vault (~50-120 μm).⁵⁸ Greater central corneal clearance has been reported for scleral lens fits for corneal ectasia compared to ocular surface disease,⁵⁹ however, this will vary with the corneal elevation (i.e. advanced cones or proud corneal grafts may require a scleral lens fit with minimal central clearance and greater clearance towards the mid-periphery or limbal region). There is some debate regarding the potential adverse effects of a thick stagnant post-lens tear layer, with excessive corneal clearance thought to possibly induce greater levels of corneal oedema in eyes with reduced endothelial cell counts. However, recent case series have shown that patients with a healthy corneal endothelium can successfully wear scleral contact lenses fitted with a wide range of central corneal clearance values (~200-2000 μm).^{59,60} Low corneal clearance may also result in adverse ocular changes during scleral lens wear such as unintentional corneal touch following lens settling, or

excessive suction in a sealed scleral system (so called “thin film adhesion”⁶¹). Tear film, suction, and landing zone forces have also been hypothesised to induce changes in corneal astigmatism and higher order aberrations that persist following lens removal.^{62,63}

Ultimately, the optimal level of corneal vault for scleral contact lens wear is the clearance that provides a stable and comfortable lens fit with good vision, minimal post-lens tear layer debris, and minimal physiological disturbance to the central and peripheral cornea for each individual patient (Figure 6). For miniscleral lens designs (total diameter up to 6 mm greater than the HVID⁵), manufacturers typically recommend an initial central clearance of ~200-400 μm to allow for ~100-200 μm of settling over the course of the day (Table 2). However, the recommended initial clearance and extent of lens settling will vary with lens diameter and design (for example, fenestrated lenses typically display substantially less central clearance after settling).

Change in central corneal clearance over time

Several studies have used anterior OCT imaging to examine the change in central corneal clearance as a function of wearing time. Bier initially observed that lenses continued to settle into the eye over the first 1-2 months of scleral lens wear,⁵⁷ however, until the advent of OCT imaging, the true dynamic nature of lens settling over the course of the day was unknown (for example, end of day settling does not appear to increase significantly following one week of lens wear).⁶⁴ Figure 7 displays the mean change in central corneal clearance over an 8 hour period for five different scleral lens designs,⁶⁵⁻⁶⁷ presented as the percentage reduction in the initial clearance since larger diameter lenses (with greater sagittal depths) typically provide greater initial corneal vault.^{59,68} The viscosity of the fluid used to fill the scleral bowl does not appear to impact lens settling in the short term⁶⁹ and while the reduction in the post-lens tear layer thickness over the course of the day does influence the optics of the combined contact lens-tear layer system, the effect is minimal (a ~0.25 D myopic shift in eyes with flat or normal corneal curvature).^{67,69,70} However, this change in

optical power is more pronounced for thicker post-lens tear layers, steeper corneae, steeper lens fits, and higher plus powers.

Due to the large variation in scleral lens settling over time between individuals and lens designs (Table 3),^{66,67,71} the end of day corneal vault should be monitored in all patients during the initial fitting and aftercare visits noting the duration of lens wear for that day. Ideally, this should be quantified using OCT (which allows the lens to remain on eye) since reinserting a scleral contact lens following removal for slit lamp examination to check for corneal staining or to add sodium fluorescein to the bowl may not result in the lens returning to the same settled position. Corneal clearance also needs to be monitored over time as settling appears to increase over the first 4-6 weeks of lens wear (based on clinical observation).⁵⁷ Patients with progressing corneal ectasia may also exhibit a reduction in central clearance over time and require regular review, since prolonged central bearing may result in corneal staining and eventual scarring.

Regional variations in corneal clearance

Figure 8 displays the corneal clearance across the central 5 mm of the cornea in an individual fitted with a miniscleral lens immediately following lens insertion and 8 hours later. A relatively symmetrical post-lens tear layer is observed along the horizontal meridian, while greater corneal clearance is present inferiorly compared to superiorly immediately following lens insertion which diminishes over time. These corneal clearance maps were generated by interpolating the post-lens tear layer thickness from 12 anterior segment OCT line scans separated by 30 degrees. Some commercial OCT instruments now include this type of analysis within their anterior segment analysis software to allow practitioners to rapidly assess central corneal clearance (e.g. iVue Vault Mapping Tool, Haag Streit).

Courey and Michaud⁶⁹ used OCT imaging to compare peripheral scleral lens settling along the horizontal meridian in healthy eyes, and observed slightly

greater settling nasally (41 μm) compared to temporally (20 μm) over 6 hours of lens wear. Otchere, Jones and Sorbara⁷² examined the symmetry of lens settling along the vertical meridian over a one hour period in eyes with corneal ectasia and observed greater settling in the inferior mid-periphery compared to the superior mid-periphery irrespective of the initial corneal vault (on average ~1.5 to 2.5x greater). Similar findings (greater nasal and inferior settling compared to temporal and superior settling respectively) have been reported in scleral lens neophytes after two hours of lens wear using Scheimpflug imaging.⁷³ These studies suggest that lenses settle more in the inferior and nasal quadrants during lens wear, however, it should be noted that scleral lens decentration (which is often infero-temporal^{67,74}) and lens tilt will also influence corneal clearance. Regional variations in lens settling are most likely influenced by a number of factors such as the method of lens insertion (for example, whether the lens is inserted under the upper or lower eyelid first), eyelid tension or pressure, the design of the landing zone and the toricity of the sclera.

The reduction in the post-lens tear layer thickness is typically 2-3 times greater centrally compared to the reduction in limbal clearance during lens wear,^{69,75} and is also greater than the magnitude of ocular tissue compression observed within the lens landing zone. This clinical observation is difficult to explain, particularly in a sealed scleral system with minimal to no tear exchange, and may be related to suction forces or circumferential mechanical pressure drawing the central cornea anteriorly slightly towards the posterior surface of the scleral contact lens.⁷⁵

Subjective estimates of corneal clearance

While OCT imaging provides the most accurate estimate of corneal clearance, not all practitioners have this technology to assess the fit of a scleral contact lens and rely upon slit lamp examination to estimate corneal clearance by comparing the thickness of the post-lens tear layer to a known reference thickness value (typically the nominal centre lens thickness provided by the lens manufacturer). Using the lens centre thickness as a reference when

subjectively estimating central corneal clearance is preferable to using the central corneal thickness (which will vary significantly between patients and with corneal location, particularly in cases of corneal ectasia). However, the true centre lens thickness may vary slightly from the published thickness value, and also varies significantly across the lens, and with back vertex power.⁷⁶ This can make the subjective estimation of limbal clearance particularly challenging. Some corneal and corneoscleral topographers provide an estimate of corneal clearance based on sagittal height data, however, the agreement between simulated post-lens tear layer profiles and corneal clearance values derived from OCT imaging has not been evaluated.

Fuller et al.⁷⁷ examined the agreement between optometry students subjective estimates of in-vivo central corneal clearance (without sodium fluorescein) compared to OCT measurements, using the corneoscleral lens centre thickness as a reference thickness value. On average, students significantly overestimated the extent of central corneal clearance, particularly for lower levels of corneal clearance (actual clearance ~100 μm , mean overestimation ~115 μm) than higher levels of corneal clearance (actual clearance ~340 μm , mean overestimation ~60 μm). Similarly, Yeung and Sorbara⁷⁸ observed a mean subjective overestimation of ~100 μm for central corneal clearance (with sodium fluorescein) based on assessments of in-vitro digital slit lamp images compared to OCT imaging across a range of apical clearance values (from 50 to 400 μm) and various levels of scleral lens fitting experience. These studies suggest that clinicians who subjectively estimate central or peripheral lens vault (with or without sodium fluorescein added to the post-lens tear layer) are more likely to dispense a lens with substantially lower than anticipated final corneal clearance. Given that the subjective estimation of corneal clearance is extremely variable compared to OCT measurements (typically an overestimate), practitioners without access to an OCT must also rely on objective clinical signs of lens bearing or adhesion following lens removal at aftercare visits (e.g. corneal staining, epithelial disruptions or indentations at the edge of the optic zone or peripheral curve junctions).

Limbal clearance

While smaller diameter corneoscleral and semi-scleral lenses with total diameters less than 15 mm will exhibit some peripheral corneal touch (assuming a ≥ 12 mm corneal diameter), for larger diameter lenses designed to rest entirely upon the sclera, peripheral corneal clearance is required to maintain limbal stem cell homeostasis. Insufficient limbal clearance or mechanical compression may result in superficial corneal staining, epithelial breakdown, rapid peripheral neovascularisation, or scarring.

A number of studies have measured corneal swelling following modern scleral contact lens wear (typically $< 2\%$ central swelling in healthy adults^{62,66,79–82}) and attribute this hypoxic response to the thickness of the contact lens and minimal tear exchange. However, mechanical factors may also contribute to scleral lens induced corneal oedema. A recent case series described various peripheral epithelial changes (negative fluorescein staining, microcystic bullae, and erosions) associated with small diameter scleral contact lenses (Figure 9), due to insufficient limbal clearance (mechanical irritation of the lens bearing on the cornea was confirmed using OCT imaging) rather than hypoxic stress alone.⁸³ However, adverse epithelial changes of a hypoxic nature may also be observed with adequate limbal clearance.⁸⁴

Conversely, excessive limbal clearance can result in bubbles within the post-lens tear layer, corneal hypoxic stress, or conjunctival prolapse. Limbal clearance can be altered by modifying a range of lens parameters including the sagittal depth of the lens or the back optic zone radius, the optic zone or total lens diameter, and the width or tangent of peripheral curves (Figure 10). The optimum or acceptable limbal clearance can vary substantially between patients, however, a maximum of 60 μm has been proposed based on theoretical modelling of corneal oxygen requirements.⁸⁵ OCT imaging is particularly useful to quantify limbal clearance since subjective estimates are much less reliable for lower clearance values,⁷⁷ and low concentrations of

sodium fluorescein may not fluoresce when the post-lens tear layer is particularly thin ($< 20\text{-}30\text{ }\mu\text{m}$).⁸⁶

The haptic or landing zone

The geometry of the landing zone of a scleral lens should align as closely as possible with the underlying ocular tissues (that is, the conjunctiva supported by the episclera and sclera) to maximise patient comfort and minimise potential physiologic and fitting complications associated with an excessively flat (for example, edge lift) or steep fit (for example, conjunctival blood vessel impingement or significant tissue compression). The width of the landing zone is also important to ensure an even distribution of bearing. While the curvature of the sclera varies markedly between ocular meridians and the distance from the limbus, many patients successfully wear rotationally symmetric lens designs. However, improved comfort and increased wearing times (2 additional hours) have been reported in patients refitted with a toric haptic design to improve scleral alignment, and promote tear exchange.⁸⁷

During an initial fitting, the relationship between the landing zone and ocular surface can be assessed using slit lamp biomicroscopy to identify any local, meridional or global regions of conjunctival compression or impingement (indicating a relatively steep peripheral curve) or edge lift (a relatively flat peripheral curve). After a period of lens wear, the practitioner can also examine any changes in superficial conjunctival blood vessels within and adjacent to the haptic zone, conjunctival sodium fluorescein staining following lens removal, and be guided by patient symptoms. Excessive tissue compression within the haptic zone typically requires flattening of peripheral curves, however, determining the appropriate magnitude of change required can be difficult and flexibility may vary between manufacturers and lens designs (Figure 11). Conversely, excessive edge lift requires steepening of peripheral curves to minimise lens awareness and patient discomfort, and reduce the potential for debris or air bubbles to enter the post-lens tear layer (Figure 12).

OCT imaging has the potential to aid the quantification of haptic zone alignment, tissue compression, and edge lift and assist with the customisation of peripheral lens designs, however, it should be noted that some degree of tissue compression will occur in successful, asymptomatic scleral contact lens wearers, with minimal conjunctival staining or complications. For example, in a short-term study using a rotationally symmetric miniscleral lens, 15 to 50 μm of tissue compression quantified using OCT imaging was observed following 3 hours of lens wear (greatest superiorly), with clinically insignificant conjunctival staining. This tissue compression within the landing zone was predominantly conjunctival (60% conjunctival compression to 40% scleral) and partially recovered by within 3 hours of lens removal (60% conjunctival and 80% scleral recovery). Changes in conjunctival morphology following lens wear may also manifest as an increase in thickness due to suction forces behind the lens, tissue inflammation, or a transient redistribution of tissue due to adjacent compression (Figure 13). Further research using OCT technology is required in order to optimise haptic alignment, minimise adverse physiologic disturbance to the ocular surface, and quantify microvasculature changes⁸⁸ within the scleral landing zone.

Scleral lens decentration

Scleral contact lenses, in particular preformed lenses, typically decentre infero-temporally,⁷⁴ most likely because of eyelid morphology and pressure, and scleral height asymmetry (the typically elevated nasal sclera). Decentration of the optic zone relative to the pupil introduces higher order aberrations that are not neutralised by the post-lens tear layer, and an unwanted prismatic effect due the change in shape of the tear lens. Lens decentration can also have adverse physiologic effects if limbal clearance is significantly reduced during lens wear. Controlling scleral lens decentration is particularly important for presbyopic corrections and customised front surface wavefront guided corrections for advanced keratoconus.^{89,90} The optical effect of lens decentration can be minimised by increasing or decentring the optic zone,

increasing the total lens diameter or incorporating a toric periphery to stabilise the lens.

OCT imaging can be used to quantify lens decentration during scleral lens wear by calculating the change in the separation between the normal to the anterior corneal apex and the normal to the apex of the anterior lens surface for line scans along the horizontal and vertical meridians.⁶⁷ Significant temporal and inferior decentration (~0.20 mm on average) occurs during the first two hours of miniscleral lens wear, then remains relatively stable once the lens has settled back into the conjunctiva (Figure 14).⁶⁷ Vincent et al reported that for a rotationally symmetric miniscleral lens (ICD 16.5), lower initial central corneal clearance values were associated with less horizontal, but not vertical, decentration.⁶⁷

IMAGING SCLERAL CONTACT LENSES

The thickness profiles of scleral contact lenses are of particular clinical interest since the centre lens thickness is often used by practitioners as a reference to estimate corneal clearance. In addition, the centre and junctional thickness will influence lens flexure, and importantly the overall lens thickness profile will influence oxygen transmission to the cornea. However, manufacturers typically only provide a lens centre thickness value (which may vary by up to $\pm 100 \mu\text{m}$ for scleral lenses and remain within the thickness tolerance for scleral lens thickness⁹¹) rather than proprietary lens thickness profile data.

Recently, Vincent et al⁷⁶ described a novel technique to measure the thickness profile of an entire scleral contact lens using OCT imaging including corrections to minimise the influence of known measurement artefacts (optical distortion and instrument assumed refractive indices). Figure 15 displays the imaging montage technique and Figure 16 highlights the variation in the thickness profile for two different scleral lens designs of similar back vertex power. This study revealed that the thickness of scleral contact lenses varies significantly with the

distance from the lens centre and the back vertex power, similar to soft and corneal rigid lenses.^{92–94} Centre lens thickness values underestimate the average lens thickness by up to 33% for high minus powers (consistent between different lens designs) (Figure 17), which has implications for accurately modelling the true global oxygen transmissibility of scleral lens systems.

This technique⁷⁶ requires a wide and deep scanning OCT imaging protocol to image an entire scleral contact lens, or post image capture processing techniques to stitch separate images together to create a montage (and account for measurement artefacts). However, in addition to the quantitative data that can be derived from OCT imaging, the en face image provide by the scanning laser ophthalmoscope can also be used as a simple qualitative clinical check during a trial fitting or aftercare visit to quickly assess lens wettability, bubble size and location for fenestrated lenses, and lens centration (Figure 18).

IMAGING BEHIND THE SCLERAL LENS

OCT imaging has enabled high resolution visualisation of the post-lens tear layer and the cornea during scleral contact lens wear, which has improved the current understanding of post-lens tear layer debris and the nature and time course of corneal oedema.

Midday fogging (post-lens tear layer debris)

OCT imaging has shed light on midday fogging; an accumulation of debris or particulate matter (potentially conjunctival lipid or mucin) within the post-lens tear layer, typically observed in ~20-30%⁹⁵ of scleral lens wearers (Figure 19). Since midday fogging can reduce contrast sensitivity and visual acuity by 1-2 lines,^{96,97} and can accumulate rapidly following lens insertion, affected patients are often required to remove, rinse, refill and reinsert their scleral contact lenses a number of times throughout the day. Some clinicians suggest that minimising corneal clearance and altering the haptic alignment can reduce midday fogging, however, Carracedo et al⁹⁷ observed no relationship between initial central

corneal vault and post-lens tear layer turbidity (particles/mm², derived from OCT image analysis). Clinically, OCT also plays an important role in differentiating a reduction in visual acuity during scleral lens wear due to either midday fogging, corneal oedema or some other aetiology.

OCT imaging to quantify scleral lens induced corneal oedema

Early reports of Fick's phenomenon or Sattler's veil associated with glass, PMMA, and low Dk RGP scleral lenses qualitatively described the incidence, onset, and duration of corneal oedema and the various attempts to eliminate it as each new lens material was introduced to clinical practice.^{98–102} Prior to the introduction of OCT imaging, Pullum et al^{103–107} used a systematic approach to quantify scleral lens induced corneal swelling in a series of studies using optical pachometry following lens removal and examined the effect of wearing time, overnight wear, lens thickness and material. However, the removal of a scleral lens to measure corneal thickness following a period of lens wear is problematic, since corneal de-swelling commences immediately following the elimination of the hypoxic stress and exposure to atmospheric oxygen. While the rate of corneal recovery following scleral lens wear has not been examined in detail using OCT imaging, based on studies using Schiempflug imaging, the cornea appears to completely recover in normal subjects within 3 hours of lens removal (following 3 hours of lens wear)⁶² with ~40% recovery observed within ~4 minutes following 8 hours of lens wear.⁷⁹ The use of OCT to measure corneal thickness without scleral lens removal overcomes this issue and is of sufficient resolution to detect subclinical corneal oedema not evident during slit lamp biomicroscopy.

Recently, Vincent et al¹⁰⁸ used high resolution OCT imaging to examine the time course and nature of central corneal swelling associated with sealed high Dk modern miniscleral contact lens wear in young healthy subjects. Corneal swelling was primarily stromal in nature, reaching a peak and plateau approximately 90 minutes after lens insertion (mean 1.36% peak stromal swelling, mean 1.18% peak total corneal swelling), with a gradual reduction in

swelling between 2-8 hours of lens wear (Figure 20). The corneal epithelium displayed an initial rapid swelling during the first 30 minutes of lens wear (a 0.56% increase in epithelial thickness), followed by a gradual decrease in thickness over the course of the day (a 2.38% reduction in epithelial thickness) consistent with the natural diurnal thinning.¹⁰⁹ This study suggests that in young healthy eyes, scleral lens induced corneal oedema is primarily stromal in nature. While epithelial oedema can occur during scleral contact lens wear, this may be a result of greater hypoxic stress associated with older materials (glass, PMMA, low Dk RGP), a compromised endothelium, mechanical stress at limbus, or the solution used to fill the lens bowl.

OCT imaging has also allowed researchers to examine the influence of apical clearance (that is, the thickness of the post-lens tear layer) upon corneal swelling. In young participants with a healthy endothelium (both normal and keratoconic corneae), substantial increases in corneal clearance appear to have a modest effect upon the magnitude of corneal swelling (tripling the thickness of the post-lens tear layer results in an additional 0.5% corneal swelling) (Table 4). However, the extent of corneal swelling will undoubtedly be exacerbated in older patients or post-graft eyes with reduced endothelial cell counts. Comparison of the time course of corneal oedema derived using OCT for lower and higher corneal clearance values to established corneal response curves for varying levels of atmospheric oxygen suggests that an increase in clearance from 230 μm to 430 μm results in a 25% reduction in oxygen reaching the cornea (from 10% to 7.5% pO_2), despite only a 0.50% increase in peak corneal oedema), consistent with measurements of oxygen tension behind high Dk scleral lenses with varying apical clearance.¹¹⁰

CONCLUSION

OCT imaging has enhanced modern scleral contact lens practice by refining initial diagnostic lens selection, accurately quantifying contact lens fit assessment, and troubleshooting fitting related ocular complications. High-

resolution imaging of the anterior segment has also advanced the current understanding of the morphology of the cornea and sclera and the physiological sequelae of scleral contact lens wear, and will undoubtedly play a role in improving future lens designs to optimise clinical outcomes.

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Table 1. Summary of studies utilising OCT imaging to quantify scleral curvature

First author	Participants	OCT imaging protocol	Fitting method	Curvature results (mm)	Comment
Hall ³³	50 healthy subjects (predominantly British Asian) 23 ± 5 years (18 - 43)	Visante (Zeiss) Primary gaze and four cardinal gaze directions	Proprietary in-built curvature correction software, to minimise potential underestimation.	Nasal: 45.0 ± 41.4 Temporal: 25.3 ± 14.8 Superior: 43.1 ± 32.2 Inferior: 42.2 ± 30.1	Repeatability of ± 7.08 mm for scleral radius.
Hall ³⁴	204 healthy subjects (predominantly British Asian) 35 ± 15 years (18 - 65)	Visante (Zeiss) Primary gaze and four cardinal gaze directions	Proprietary in-built curvature correction software, to minimise potential underestimation.	Nasal: 35.5 ± 39.4 Temporal: 22.4 ± 12.7 Superior: 29.3 ± 17.4 Inferior: 33.5 ± 29.6	Significant negative association between scleral curvature and age (steeper with increasing age).
Choi ³⁸	24 healthy Koreans 31 ± 7 years (24 - 54)	Visante (Zeiss) Composite image (central, nasal, temporal)	BFC: the curvature of the best fit circle through the limbus and points 1,2,3 mm posterior to the limbus nasally and temporally. Axial: the distance along the normal from the scleral tangent 2mm from the limbus to the optical axis.	BFC: 13.12 ± 0.80 Nasal: 13.33 ± 1.12 Temporal: 12.32 ± 0.77	Good repeatability. Underestimation of RGP corneal contact lens curvature by 0.1-0.2 mm despite software correction of curvature distortion.
Kasahara ³⁶	34 healthy subjects (Japan) 63 ± 16 years (28 - 84)	CASIA SS-1000 (Tomey) Superonasal and superotemporal	Two point fit between the scleral location intersecting the normal to the scleral spur and the tangent to the anterior sclera and a point 5 mm away.	Superonasal: 34.3 ± 12.6 Superotemporal: 18.3 ± 3.6	Good repeatability. No correction/calibration against know ROC.
Lee ³⁵	24 healthy Koreans 31 ± 7 years (24 - 54)	Visante (Zeiss) Composite image (central, nasal, temporal)	Curvature calculated using 8 th order polynomial with at 16 mm chord.	Nasal: 13.68 ± 0.71 Temporal: 11.73 ± 0.61	Nasal-temporal curvature asymmetry increases with chord length ~15 mm nasal to 12.3 mm temporal over an 18 mm chord.
Bandlitz ³⁷	30 healthy students (Germany) 24 ± 2 years	Optos OCT/SLO (Optos) Cardinal gaze directions	Three point circle fit along each hemi-meridian.	Nasal: 35.29 ± 17.68 Superonasal: 74.57 ± 45.97 Superior: 45.00 ± 31.99 Superotemporal: 29.41 ± 7.70 Temporal: 24.40 ± 4.86 Inferotemporal: 27.17 ± 5.90 Inferior: 31.42 ± 13.44 Inferonasal: 36.46 ± 34.64	Good repeatability. Measurements of scleral curvature measurements calibrated using glass beads of known curvature.

BFC: best fit circle

Table 2. Manufacturer recommendations for scleral lens clearance

Manufacturer/Distributor	Lens (diameter, mm)	Fitting guide corneal clearance comments
Accu Lens	Maxim (15.4 - 21)	250 µm initial clearance over the steepest part of cornea and 150 µm after settling
	Comfort SL (16.2 - 16.7)	150 µm after settling
	EasyFit (14 - 15.5)	100 - 150 µm after settling
Advanced Vision Technologies	AVT Scleral (15 - 22)	~250 - 350 µm after at least 15 minutes of wear
Alden Optical	Zenlens (16, 17)	300 - 400 µm initial clearance
ART Optical	AmplEye Scleral (15 - 16.5)	250 - 400 µm pre-settling over the highest point of the cornea and 125 - 275 µm after 8 hours settling
Blanchard Contact Lenses	MSD Select (15.8, 18)	175 - 250 µm after a few hours of settling
	Onefit MED (15.6 - 16.4)	250 - 275 µm at the point of highest corneal elevation initially and 150 - 175 µm after 4+ hours of wear. Mid-peripheral clearance 100-125 µm and limbal clearance 50 - 75 µm after 4 hours wear.
BostonSight	Scleral (18, 18.5, 19)	200-300 µm clearance desired
Capricornia Contact Lenses	KATT (16.5)	~300 µm initial clearance
Essilor	Jupiter (15 - 20.8)	Ideal clearance is generally 200 - 400 µm
Gelflex	Sealed Miniscleral (14 - 26)	~300 µm apical clearance
GP Specialists	iSight Scleral (14.2 - 24)	300 - 350 initial clearance and ~150 - 250 µm after settling
Innovative Contacts	EyeSpace Scleral (16.5, 17.5)	200 - 300 µm initial apical clearance, no less than 100 µm after settling
Metro Optics	InSight Scleral (13.5 - 20)	Ideal 150 - 300 µm
	Genesis Scleral (13.5 - 24)	Ideal 100 - 300 µm
Paragon Vision Sciences	ICD (14.8, 16.3)	Ideal initial clearance 300 µm

SynergEyes	SynergEyes VS (14 - 17.5)	Ideal fit ~200 µm central clearance after settling (ideal limbal clearance ~100 µm)
Valley Contax	Custom stable (14.8 - 17.8)	150 - 250 µm
Visionary Optics	Europa Scleral (16, 18, 20)	100 - 300 µm
	Elara Scleral (15.5)	Final vault central 200 µm
	Jupiter Scleral (13.5 - 24)	Ideal fit 40 - 200 µm corneal clearance
X-Cel Speciality Contacts	Atlantis (15 - 17.5)	~200 µm clearance over the most elevated portion of the cornea

Table 3. Summary of studies examining scleral contact lens settling using OCT imaging.

First author	OCT	Participants	Lens design (total diameter mm)	Wearing time (hours)	Key findings
Caroline ⁷¹	Visante (Zeiss)	15 healthy subjects	ICD(16.5)	8	Wide intersubject variation; mean settling 96 μ m, range 70-180 μ m.
Kauffman ⁶⁵	Cirrus (Zeiss)	8 healthy subjects > 18 years	Onefit P&A (14.3) MSD (15.8) Jupiter (18.2)	8	Two phase exponential decay in settling (majority within 2 hours, stable after 4h). Total settling greater for smaller diameter lens (15.8 vs 18.2 mm).
Bauer ⁶⁴	Spectralis (Heidelberg)	6 subjects (12 eyes)	MSD (15.8)	8 (5 days)	Biphasic exponential decay in settling (50% of 8 h settling after 1 h). No difference in 8h CCC between day 1 and day 5.
Vincent ⁶³	RS3000 (Nidek)	15 subjects (8 Asian, 7 Caucasian) 22 $\pm$ 1 years	ICD (16.5)	8	Greater settling observed in Asian (110 $\pm$ 10 μ m) compared to Caucasian eyes (80 $\pm$ 23 μ m).
Esen ⁶⁶	RTVue (Optovue)	11 keratoconics (22 eyes) 28 $\pm$ 8 years	Esclera (16.5 & 17.5)	8	Exponential decay in settling (43% of total settling after 1 hour, 81% in 4 h). Greater settling with smaller diameter lens (17.5 mm vs 16.5 mm). Greater settling with greater initial CCC (>200 μ m vs < 200 μ m).
Bray ⁷⁰	Visante (Zeiss)	16 subjects 25 $\pm$ 2 years	MSD (15.8)	6-8	Reduction in CCC of 83 $\pm$ 22 μ m associated with minimal change in over refraction for normal/flatter corneae.
Rathi ⁵⁹	Visante (Zeiss)	41 patients (50 eyes) (20 ectasia, 30 OSD) 31 years	PROSE (16 – 18.5)	4	Greater initial CCC in ectasia 759 $\pm$ 574 μ m compared to OSD group (626 $\pm$ 276 μ m). Greater settling in the ectasia (125 μ m, 17%) compared to ocular surface disease group (68 μ m, 14%).
Courey ⁶⁹	Optovue (Clarion)	15 subjects (30 eyes) 27 - 46 years	MSD (18)	6	No effect of post-lens tear layer fluid viscosity upon settling dynamics. Greater nasal settling compared to temporal (23 $\pm$ 7 μ m more).
Otchere ⁷²	Custom built long wavelength	20 subjects with corneal ectasia 34 $\pm$ 8 years (23 - 51)	Jupiter (15)	1	No significant difference in settling between different initial CCC groups (200, 400, 500 μ m). Greater inferior and superior settling for lenses fitted with larger initial CCC.
Vincent ⁶⁷	RS3000 (Nidek)	15 subjects 22 $\pm$ 1 years	ICD (16.5)	8	Exponential decay in settling (50% of total settling after 45 minutes, 75% in 2h). No association between initial CCC and total settling over 8 h. No association between settling and lens decentration.

CCC – central corneal clearance, ICD – irregular corneal design, MSD – mini scleral design, OSD – ocular surface disease, PROSE - prosthetic replacement of the ocular surface ecosystem

Table 4. Summary of studies examining the effect of corneal clearance on central corneal oedema (data presented is the mean $\pm$ the standard error).

First author	Central clearance (μm)	Central oedema (%)	Notes
Arlt ⁸⁰	Low (209 ± 30)	1.59 ± 0.35	Initial clearance and oedema after 8h extracted from raw data
	High (630 ± 25)	1.76 ± 0.48	
Esen ⁶⁶	Low (100 to 200)	2.30	Initial clearance and oedema after 8h (extracted from Figures)
	Medium (200 to 300)	1.48	
	High (>300)	1.42	
Vincent ¹⁰⁸	Low (225 ± 21)	0.95 ± 0.33	Initial clearance and peak oedema (90 mins)
	High (431 ± 26)	1.37 ± 0.26	
	Low (156 ± 14)	0.34 ± 0.25	Clearance and oedema after 8h
	High (350 ± 29)	0.65 ± 0.48	
Tan ⁸²	Low (<150, 103 ± 5)	1.43 ± 0.23	Clearance and oedema after 5h (extracted from Figure 3)
	Medium (150 to 300, 216 ± 7)	1.46 ± 0.21	
	High (>350, 367 ± 9)	1.54 ± 0.24

Figure 1. A high resolution cross sectional image of the human cornea (an average of 30 B-Scans) (top) and thickness maps of the total cornea and epithelium across the central 7 mm derived from the interpolation of 12 radial OCT line scans (bottom).

Figure 2. An example of tissue compression and strain during miniscleral contact lens wear immediately following lens insertion and 60 minutes later. Stress lines are visible directly beneath the haptic landing zone and the adjacent scleral tissue (red box) neighbouring Schlemm's canal (blue box).

Figure 3. OCT images of the temporal (top) and nasal (bottom) corneoscleral region from the same eye. The nasal image displays a tangential (straight) transition from the cornea to the sclera and a relatively flat scleral profile, while the temporal image highlights a sharper and more apparent corneoscleral junction angle and a steeper scleral curvature.

Figure 4. (A) The corneoscleral junction angle (CSA), defined as the angle formed by the anterior corneal (red line) transition into the anterior sclera (conjunctiva) (blue line) and (B) the corneal (red) and scleral (blue) sagittal depth measured at the corneal diameter and a 15 mm chord respectively. The yellow line represents the approximate limbal zone (transition from cornea to sclera), the green line represents the corneal apex and the white line represents the tangent to the corneal apex.

Figure 5. Frequency histograms of the corneoscleral junction angle along the nasal, temporal, superior and inferior meridians derived using OCT imaging. The corneoscleral junction is typically straight for the temporal, superior, and inferior meridians ($180 \pm 2.5^\circ$), but more variable along the nasal meridian with a less obtuse angle indicating a more rapid deviation in scleral curvature closer to the limbus. The black line (180°) represents a tangential extension of the peripheral cornea to the sclera. Adapted from Hall et al³⁴ (A) (measured at a chord length equal to the corneal diameter for each subject), and Ritzmann et al⁴⁰ (B) (measured at a set 12.8 mm chord).

Figure 6. Example OCT line scan images demonstrating variation in initial central clearance for a various miniscleral contact lenses of different sagittal depths fitted to a normal cornea (A) 150 μm , (B) 250 μm and (C) 400 μm apical clearance.

Figure 7. The change in central corneal clearance for five different diameter miniscleral contact lenses over an 8 hour period in normal healthy eyes measured with an anterior segment OCT.^{65–67} The majority of lens settling occurs within the first 2 hours of lens wear, with minimal changes between 2 and 8 hours. Smaller diameter lenses (<16 mm) exhibit greater settling compared to larger diameter lenses (>16 mm).

Figure 8. Corneal clearance maps (the post-lens tear layer thickness) for one individual derived from the interpolation of 12 radial line OCT scans separated by 30 degrees across the central 5 mm centred on the pupil. A marked asymmetry is seen along the vertical meridian immediately following miniscleral lens insertion (excessive infero-temporal clearance) (A) which diminishes after 8 hours of lens wear following lens settling (B).

Figure 9. Inferior limbal microcystic corneal oedema and negative sodium fluorescein staining in a scleral contact lens wearer despite adequate limbal clearance (Image courtesy of Jimmy Tse).⁸⁴

Figure 10. Example OCT images highlighting variations in peripheral corneal and limbal clearance in the same eye for alternative lens designs ranging from peripheral lens bearing (top), 75 μm (middle), and 120 μm limbal clearance (bottom).

Figure 11. An example OCT image of a harsh landing of a miniscleral contact lens (abutting the conjunctiva) (A) and a softer landing more closely aligning with the underlying ocular shape (B).

Figure 12. An example OCT image of a corneoscleral contact lens with peripheral corneal alignment and excessive edge lift (A) and minimal edge lift (B).

Figure 13. Two examples of tissue compression following three hours of sealed miniscleral contact lens wear. (A) Conjunctival compression evident at the landing zone following lens removal with perilimbal conjunctival thickening, most likely due to negative pressure behind the lens. (B) Conjunctival compression at the landing zone and thickening beyond the landing zone (conjunctival redistribution) following lens removal. The red line denotes the anterior cornea and conjunctival surface, the blue line denotes the posterior corneal and scleral surface, and the dashed green line marks the scleral spur for image alignment.

Figure 14. The mean horizontal and vertical lens decentration for 15 subjects with normal cornea wearing a rotationally symmetric ICD 16.5 miniscleral contact lens over an 8 hour period (adapted from Vincent et al⁶⁷). Negative y-axis values denote inferior and temporal decentration.

Figure 15. Example of OCT image stitching and segmentation process combining three line scans taken at different depths (images 1, 2 and 3 in A) in order to quantify scleral lens thickness across the entire lens (after Vincent et al⁷⁶). (B) The final stitched image and (C) the final stitched imaged with the anterior (red) and posterior (green) lens surfaces manually segmented.

Figure 16. The thickness profile of a corneoscleral (6.9/14.6/-6.75 Rose K2 XL) and miniscleral contact lens (6.75/16.5/-6.87 ICD) of similar back vertex power following correction of image distortion. Lens thickness varies significantly with eccentricity and lens design, with the thinnest aspect of the lens observed centrally or at the lens edge (for minus powered lenses), and the thickest aspect at the edge of the optic zone.

Figure 17. The relationship between the difference in centre and average scleral lens thickness with back vertex power for a semi-scleral (Rose K2 XL) and miniscleral design (ICD). For higher minus back vertex powers, the centre thickness significantly underestimates the average lens thickness (after Vincent et al⁷⁶).

Figure 18. Optical coherence tomography scanning laser ophthalmoscope images of a poorly wetting scleral contact lens during a trial lens fitting (A), and an evenly dispersed tear film of a wettable scleral contact lens (B) in the same patient. Panels (C) and (D) demonstrate inferotemporal decentration of the optic zone (dashed red line) relative to the pupil (solid blue line).

Figure 19. Example OCT line scan image highlighting debris within the post-lens tear layer.

Figure 20. The mean change in the central cornea (epithelial, stromal and total corneal thickness) during high Dk miniscleral contact lens wear in young healthy eyes, measured with a high resolution OCT (after Vincent et al¹⁰⁸).