Clinical highs and lows of Dk/t

Part 1 – Has oxygen run out of puff?

In the first of a two-part series, **Professor Noel Brennan** and **Dr Philip Morgan** look at the latest terminology and theories about oxygenation of the cornea through silicone hydrogel lenses

Although silicone hydrogel (SiH) contact lenses have fallen short of their original goal, solving the continuous wear-infectious keratitis problem, they undeniably provide a superior environment than hydrogels by promoting normal corneal metabolic activity. While there is consensus on this benefit, it is less clear how high we have to go in terms of oxygen transmissibility (Dk/t) within the SiH category to achieve an optimal physiological result. (For simplicity, units of 10^{-9}(cm/sec)(mlO_2/ml.mmHg) are omitted where Dk/t values are given in the text.) Theoretical modelling backed up by equivalent oxygen percentage (EOP)-based empirical data suggests that there will be little difference between any of the SiH lenses.[1-6] However, some authors argue that one should expect continuing benefits by increasing Dk/t within the SiH range.[7-9]

While the modelling and laboratory findings are important to contemplate, the ultimate test of these differences will be found in clinical performance. In this, the first of a two-part series, we address the clinical perspective to arrive at the conclusion that there is little to be gained in strict physiological terms by pushing Dk/t values beyond those provided at the low end of the SiH range. In part two, we will highlight important differences in performance within the SiH category that are not oxygen based and should be the real consideration for selecting between different lens brands.

The law of diminishing returns

The law of diminishing returns must apply when considering the relation between oxygen reaching the cornea and Dk/t. Let us suppose a contact lens with Dk/t equal to 100 leads to a partial pressure of oxygen at the front surface of the cornea of 100mmHg (from available data, this is most probably a conservative estimate). Under normal open eye wearing conditions, doubling the Dk/t to 200 will not lead to a partial pressure of 200mmHg. It cannot, because the partial pressure of atmospheric oxygen at sea level is about 159 mmHg (at STP) and the pO_2 at the corneal surface will never exceed this. We can keep doubling the Dk/t, but it will never lead to a pO_2 of greater than that in the atmosphere. Data from Bonanno *et al* in Figure 1 exemplify this by showing that pO_2 at the anterior surface increases only gradually above a Dk/t level of about 85.[10]

Figure 2 demonstrates that as the modelling of corneal oxygenation from Dk/t to EOP to flux to consumption

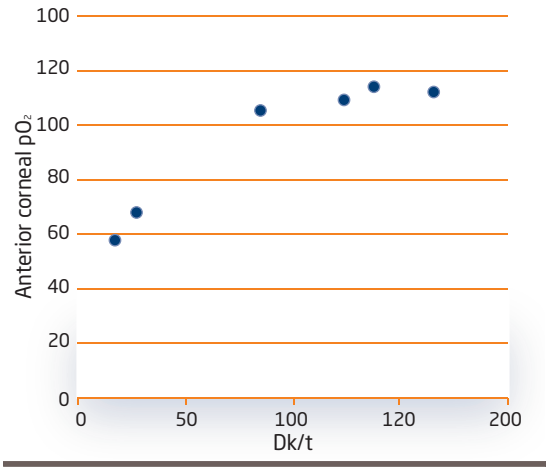

Figure 1 Open eye pO_2 estimates from a phosphorescent dye technique[10]

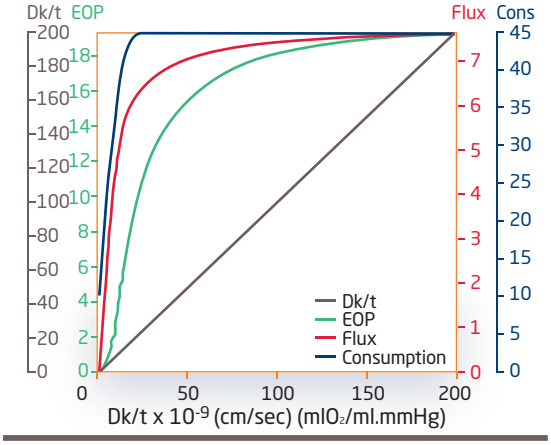

Figure 2 Combined graph showing Dk/t, EOP, anterior corneal oxygen flux (Flux; µl/cm^2 hr) and Consumption (Cons; nl/cm^3 sec) as a function of Dk/t for the open eye calculated according to Brennan.[2] Different y-axis scales are provided for each of these variables

WHICH SCALE BEST DESCRIBES CORNEAL OXYGENATION?

When we talk about corneal oxygenation, what we really want to know is the amount of energy that the cornea is generating to carry out its normal functions.

Since oxygen flow is the rate-limiting step we know that this will be directly proportional to the rate of oxygen metabolism (or consumption) through the Kreb's TCA cycle and the electron transport chain. Before the advent of silicone-hydrogel lenses, soft lens Dk/t was limited to about 30. At this low level of oxygenation, Dk/t was a useful *de facto* index because the relationship between metabolism and Dk/t is essentially linear for this small section of the curve. But while Dk/t tells us exactly how much oxygen passes through a contact lens on the laboratory bench, that does not replicate the on-eye situation. Many people also used equivalent oxygen potential or percentage (EOP), which predicts the partial pressure of oxygen at the front surface of the cornea. However, the relation between partial pressure and metabolism is ultimately not linear as it follows a relation called Michaelis-Menten kinetics.

Fatt suggested using anterior corneal oxygen flux,[11] commonly referred to simply as 'flux', as this tells the volume of oxygen that enters the cornea. While this is a much-preferred index to EOP and Dk/t, it falls short of being a perfect index of metabolism because oxygen can also move across the posterior surface of the cornea. Ultimately, we want a means of determining the primary variable of interest and 'oxygen consumption' provides this; it is equivalent to the net flux, or the sum of the fluxes at front and back corneal surfaces. Currently, the best method available for assessing consumption is by using Fatt's method of diffusion equations.[12]

Figure 2 demonstrates how the law of diminishing returns becomes more apparent as we increase the degree of sophistication of the estimators from Dk/t to EOP to flux to consumption.

TABLE 1

Select SiH and hydrogel contact lens material properties. Maximum and minimum Dk/t values are derived from various sources including manufacturer data*, Bruce,[13] Efron *et al*[14] and our own unpublished measures†

Material	Brand name	Water content (%)	Modulus (MPa)	Maximum Dk/t *,13,14,†	Minimum Dk/t *,13,14,†	Surface modification	Other technology
Asmofilcon A	PremiO	40	1.07	161	70	Nanogloss plasma coating	Menisilk
Balafilcon A	PureVision	33	1.06	84	38	Plasma oxidation	
Comfilcon A	Biofinity	48	0.75	145	64	None	Aquaform Technology
Enfilcon A	Avaira	46	0.5	125	55	None	Aquaform Technology
Filcon II 3	Clariti	58	0.5	86	?	None	Aquagen Process
Galyfilcon A	Acuvue Advance	47	0.43	107	37	None	Hydraclear Technology
Iotrafilcon A	Night & Day Aqua	24	1.5	203	68-140	Plasma-polymerisation	Aqua moisture system
Iotrafilcon B	Air Optix Aqua	36	1.2	101	45	Plasma-polymerisation	Aqua moisture system
Narafilcon A	1-Day Acuvue TruEye	46	0.66	118	47	None	Hydraclear 1 Technology
Senofilcon A	Acuvue Oasys	38	0.72	153	74	None	Hydraclear Plus Technology
Etafilcon A	Acuvue 2	58	0.3	26	8	None	
Omafilcon A	Proclear	62	0.49	29	11	None	

becomes more sophisticated, continuing to increase Dk/t shows increasingly marginal benefits (see panel). Hence, there is no question that the law of diminishing returns applies, the only real question is, at what point do increases in Dk/t cease to have real clinical benefit? Research on oxygen consumption and the clinical evidence presented below suggests that this level is below the lowest Dk/t value found in SiH lenses.

In analysing the implications of oxygen on corneal tissue, it is appropriate to refer to a set of lens parameter values. Such information is provided in Table 1. It should be remembered that the Dk/t value cited for most lenses applies to the centre of the lens alone. A lens with a central Dk/t of 20 may well have a peripheral Dk/t of 10 or less.[13] Central and peripheral Dk/t values provided in Table 1 are estimates derived from various sources of permeability and thickness values, including manufacturer data, Bruce, Efron *et al* and our own unpublished measures.[13,14] Maximal Dk/t data may vary from manufacturer stated values as these are commonly presented at -3.00D.

A common clinical interpretation is that power variations cause major changes in Dk/t; in truth, the manufacturers are skilled at keeping maximum thickness values below about 0.30mm across a wide range of powers and this rule-of-thumb can be useful for estimating the worst case Dk/t on higher-powered lenses. For speciality lenses, such as torics, the same maximal thickness values will tend to apply, so the general conclusions made in this paper for spherical lenses will be generally applicable to speciality lenses.[15] Dk/t values used in the discussion below will refer to central Dk/t unless otherwise stated. Acuvue Advance and PureVision exhibit minimum Dk/t data for SiH lenses generally recommended for daily wear (DW) and continuous wear (CW) respectively and these lenses will be referred to in this context below.

Known oxygen-related effects

Realistically, all hydrogel lenses induce corneal hypoxia. Short-term closed eye wear of hydrogel lenses leads to corneal œdema,[16,17] limbal hyperæmia[18,19] and endothelial blebs.[20] A period of hydrogel lens CW sees the development of microcysts and vacuoles,[21,22] vascularisation of the cornea,[18,21] stromal thinning,[23] endothelial polymegethism,[24] and myopic creep.[25]

Open-eye wear of hydrogel lenses produces less effect than closed eye wear but evidence suggests that there is virtually always some degree of hypoxia somewhere in the cornea. Limbal hyperæmia is the most obvious sign and occurs in most people during hydrogel lens wear.[26,27] Long-term DW of hydrogel lenses has also been shown to cause endothelial polymegethism,[28] but it is unclear whether the extent is uniform across the oxygen transmissibility (Dk/t) range of hydrogels (about 0 to 30) as studies to date have only considered the various modalities by group. Lower Dk/t hydrogel lenses (less than about 20) are known to cause corneal swelling even with the eyes open.[29] Lenses at the low end of the Dk/t range (a peripheral Dk/t of less than about 10) may also lead to vascularisation.[30-32] It is therefore likely that lenses at the upper end of the Dk/t range (above a Dk/t of about 20) produce minimal change to the cornea aside from limbal hyperæmia. Since most contact lens wearers around the world use thin, medium-water content hydrogel lenses with a central Dk/t of 20 or thereabouts, it is reasonable to state that elimination of limbal hyperæmia constitutes the outstanding, if not only, reason for switching from DW hydrogels to SiH lenses.

Oedema, striae and endothelial folds

There is a strong link between the thickness of the cornea and its oxygen supply.[33,34] During open-eye wear, the cornea will swell if the contact lens Dk/t is under about 20.[35] Hydrogels will therefore generally produce some ▶

corneal swelling even when the eyes are open. If this amount is more than about 5 per cent, the clinician will also be able to see posterior stromal striae and when it swells by more than about 10 per cent, endothelial folds appear.[36] None of the SiH lenses would be expected to produce any corneal swelling while the eyes are open and there is evidence to support this contention.[37]

During overnight eye closure, there will be some swelling of the cornea even without contact lens wear. The amount has been estimated to be between 0.7 and 5.5 per cent.[38] The amount varies with lens wearing experience; Cox *et al* found 3.8 per cent swelling in non-contact lens wearers, 2.0 per cent in subjects adapted to DW hydrogel lenses and 0.7 per cent in those adapted to CW hydrogel lenses.[39] All contact lenses will cause further swelling in the closed eye state above these baselines. Thin, medium-water content hydrogels will generally cause about 8 per cent further swelling and hydrogels with lower Dk/t than these will cause greater amounts.[40] SiH lenses cause much less œdema. The SiH lens with the lowest Dk/t that is approved for CW, PureVision, only causes about 2 per cent swelling additional to the baseline amount.[40] The SiH with the highest Dk/t, Focus Night & Day, causes about 1 per cent more swelling.[41] It is unclear whether these small amounts of 1 to 2 per cent swelling seen with SiH lenses in addition to that which occurs without a contact lens in place are indicative of harmful hypoxic stress and whether the small differences between these lenses are important. In the absence of a known link between swelling and corneal pathology and given the large proportional difference between SiH and hydrogel lenses, we propose that the degree of swelling occurring with SiH lenses is of no consequence.

Microcysts

Holden *et al* stated that, of various compromises that CW of hydrogels may produce, 'the most easily observable condition indicative of epithelial compromise is microcysts'.[42] Sweeney *et al* state that 'in clinical trials microcysts are used as the classic marker of hypoxia'. Hickson and Papas measured the incidence of microcysts in people who do not wear contact lenses to be 49 per cent, although none showed more than 5 microcysts per cornea.[43] DW of hydrogel lenses does not seem to influence this incidence;[42,44] consequently DW of SiH lenses would not be expected to increase this prevalence, a premise based on the default that no-one has deemed it worthy of measuring.

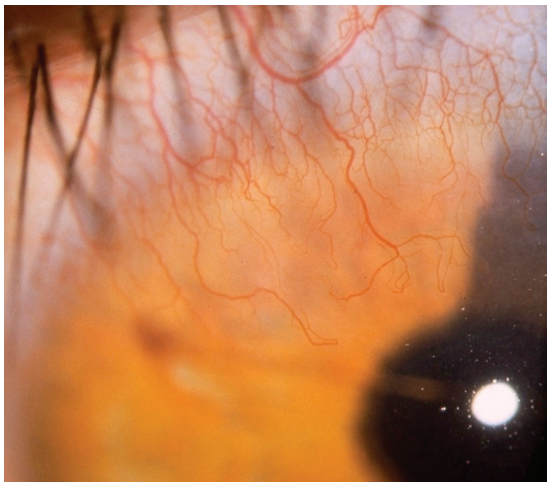

Figure 3 SiH contact lenses do not appear to induce vascularisation (shown here) at all

In contrast, the mean number of microcysts in subjects wearing hydrogel contact lenses after five years of CW has been reported as 17 ± 21, with virtually all eyes showing at least one microcyst.[23] Microcyst numbers inversely correlate with Dk/t during closed eye wear, with the Dk/t level at which they fall to baseline numbers estimated at around 50.[45] Given that the central Dk/t of the PureVision is about 90, it is no surprise that microcysts are not generally reported as a problem with SiH lenses. Brennan *et al* reported on wear of 3 different type of SiH lenses and found an incidence of 30 to 59 per cent, which is consistent with the Hickson-Papas baseline but a higher incidence of 9 to 17 per cent with greater than 10 microcysts.[46] They studied the lenses with highest and lowest Dk/t values in the EW category for SiH but found no evidence of a relation between this most important marker of hypoxia and Dk/t within this group.

Vascularisation

Vascularisation is important because it is the only, serious, contact lens-related threat to vision other than microbial keratitis (Figure 3). It can occur with both DW and CW of hydrogels. Because it takes some time to develop and is non-acute in nature, incidence and relative risk data are very patchy. Lenses with even modest peripheral Dk/t values, say around 10 as is found in some thin high-water content lenses, may induce some minor sprouting of vessels but do not appear to induce significant vascularisation in DW. It is therefore most unlikely that any hypoxic related vascularisation would be found with SiH lenses in DW and we are unaware of any such reports.

Dumbleton *et al* considered vascularisation over nine months of CW and found significant vascularisation in wearers of low Dk/t lenses (peripheral Dk/t about 10) and none in wearers of high Dk/t (peripheral Dk/t values in the region of 60 to 100) lenses,[47] confirming the general relation between vascularisation and Dk/t. However, there have been very few studies enabling assessment of the impact of Dk/t within the SiH category. Over a period of one year of CW, Brennan *et al* found near zero percent incidence of significant vascularisation in either eye among 212 subjects wearing PureVision and Acuvue lenses contralaterally.[48]

Further analysis of a one-year CW study of PureVision, Night & Day and Biofinity reported by Brennan *et al*[46] found that almost half of the subjects, who were from a mixed history of previous wear, were graded as having some degree of vascularisation on entry to the study. At subsequent visits, recorded vascularisation decreased considerably but more or less equally between the different lens types. At the final visit, 25 per cent of subjects wearing PureVision still showed some degree of vascularisation versus 21 per cent of subjects wearing Night & Day. Santodomingo *et al* do not even mention vascularisation in their 18-month comparison of PureVision and Night & Day, restricting comments entirely to hyperæmia.[49,50]

In summary, SiH lenses seem to have eliminated hypoxically-induced vascularisation. Further, there is no evidence of differences within the SiH category with regard to propensity to induce vascularisation.

Limbal redness

As noted earlier, limbal redness is the primary hypoxic sign in DW of thin, medium water content, hydrogel lenses. Papas derived a critical peripheral lens Dk/t value of 125 to avoid limbal redness in open eye wear[51] and this proposal is one of the main pillars for advocates of higher Dk/t. However, the methodology used to derive this criterion has shortcomings. In keeping with Holden and Mertz,[35] the mathematical approach seeks to identify an intercept between what is essentially an asymptotic curve and its asymptote, an inherently imprecise exercise. There are also serious doubts over the quality of the control used by Papas. The baseline was taken to be the eye without a contact lens. But mechanical effects and temperature during lens wear may confound limbal redness measures over ▶

and above the influence of Dk/t.

To this end, we surveyed the literature for support to Papas' criterion of 125. Our search identified seven studies that compared differences between two different SiH lenses in the degree of induced limbal hyperæmia in both DW and CW.[46,49,52-56] Since the peripheral Dk/t values of all the SiH lenses fall below 125 and no two values are the same, we would expect to find significant differences in the degree of limbal redness in all of these studies if Papas finding is clinically important. In none of these studies was there a difference reported. This suggests that, not only is the criterion of 125 of little relevance in the clinical world, but that a figure of 37, the minimum peripheral Dk/t found in DW silicone-hydrogel lenses, is adequate to avoid clinically important open-eye limbal redness.

Endothelial blebs

Within minutes of insertion of a contact lens, dark regions known as blebs appear in the specular reflection of the endothelium[20](Figure 4). Although they are not regarded as being of pathological concern on their own, blebs constitute an immediate index of hypoxia with the area of the endothelium comprising blebs during wear of a contact lens being inversely proportional in general to the Dk/t of that lens.[57] However, we recently tested whether there were differences in bleb response within the SiH category. We examined bleb formation following 20 minutes wear of SiH lenses in East Asian eyes under open and closed eye conditions and were unable to demonstrate differences across Dk/t.[58]

Endothelial polymegethism

Most studies agree that endothelial cell density is not affected by either daily or continuous contact lens wear; however, the distribution of cell sizes and shapes does change, effects known as polymegethism and pleomorphism respectively. Of the clinical markers that potentially indicate long-term physiological compromise to the cornea through chronic hypoxia, endothelial polymegethism would seem to be the most sensitive. Microcyst numbers tend to peak after several months of CW (not counting the rebound effect if this mode of wear is interrupted), stromal and epithelial thinning are generally modest in magnitude compared to population variance, vascularisation only arises in individual cases and usually requires severe hypoxia but polymegethism seems to continue to worsen linearly over time.[28,59,60] It also seems to increase with intensity of wear.[59] Figure 5 shows the endothelial appearance of a 25-year veteran hydrogel lens wearer compared to young and older non-wearers. The development of endothelial polymegethism appears to be related to the degree of hypoxia as there is considerable change in wearers of PMMA lenses, during CW of hydrogel lenses and to a lesser extent in DW of hydrogel lenses;[24,61,62] however, there is minimal change in wearers of silicone elastomer lenses.[63] Yet, it is unclear at what Dk/t level polymegethism begins. It is also yet to be determined whether SiH lenses induce this phenomenon and also whether switching to these materials allows recovery from hydrogel lens induced endothelial polymegethism.

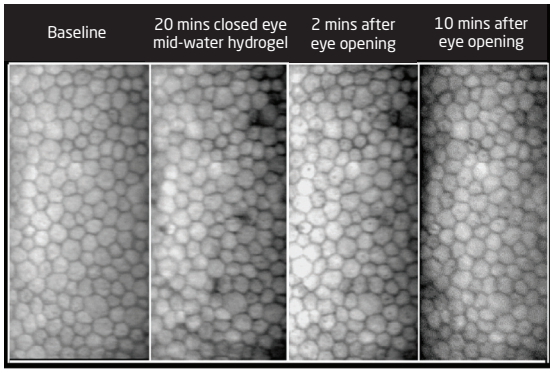

Figure 4 Endothelial photomicrographs showing a development and resolution of blebs with closed eye hydrogel lens wear at a single site (note matching cells between photographs). A new, interesting finding is the apparent increase in the number and clarity of central dots just after the stimulus is removed. SiH lenses cause minimal bleb response in the open or closed eye

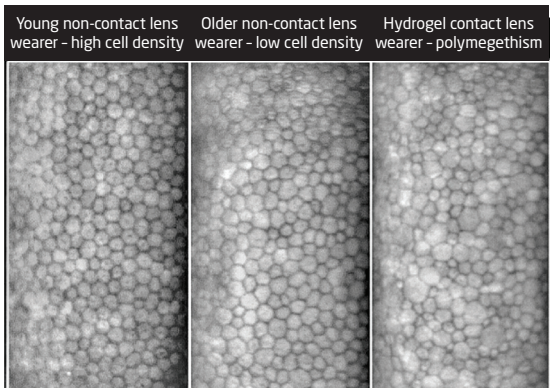

Figure 5 Endothelial photomicrographs showing normal cell density and high regularity in a six-year-old, lower cell density and increasing irregularity in a 49-year-old, and polymegethism in a 25-year-old veteran wearer of hydrogel contact lenses. We await the results of research to demonstrate whether SiH lenses cause endothelial polymegethism

Corneal thinning

Both epithelial and stromal thinning may occur in response to CW of hydrogel lenses[23] but an effect with DW is less obvious.[64,65] It is uncertain how much of the thinning can be attributed to mechanical effects as opposed to hypoxic effects. Orthokeratology is known to thin the cornea centrally[66] and the majority of this effect is independent of Dk/t. There is no evidence that there is hypoxic related corneal thinning with SiH lenses.

Myopic creep

Small myopic shifts have been previously identified with DW and CW wear of hydrogel lenses and the degree to which these occur would seem to be greater than with spectacles.[67,68] These changes are not apparent with wear of at least one brand of silicone-hydrogel lens.[25,69] However, the degree to which myopic changes are attributable to hypoxia remains open to conjecture. There is no apparent increase in central corneal curvature associated with hydrogel lens-induced myopic shift.[70] It is theorised that peripheral retinal refraction is responsible for ocular growth.[71] Wear of standard design contact lenses may change the aberration profile leading to a greater degree of optically stimulated myopic increase than if spectacles were worn. This effect may be counterbalanced in the case of wear of higher modulus silicone-hydrogel lenses, which will have a tendency to mechanically flatten the central cornea region.[72]

Summary

There is little evidence of physiologically-based performance variation within the silicone-hydrogel lens category. That which is known to exist comprises small differences of unknown significance in the closed eye corneal swelling response between SiH lenses and laboratory differences in limbal hyperæmia that do not seem to manifest in clinical reports for either DW or CW. In part two of this series, we will consider those differences in lens performance between SiH brands which are important and show that these are related to material properties other than oxygen transmissibility.

This article was originally published in Optician, 2009, Vol 238, No 6209, 16-20

Professor Noel Brennan is general manager of Brennan Consultants Pty in Melbourne Australia and adjunct professor at Queensland University of Technology. **Dr Philip Morgan** is a senior lecturer in optometry, and is director of Eurolens Research, at the University of Manchester

Clinical highs and lows of Dk/t

Part 2 – Modulus, design, surface - more than just fresh air

In the second part of a two-part series, **Professor Noel Brennan** and **Dr Philip Morgan** look at the clinical behaviour of silicone hydrogels based on characteristics other than oxygen performance

The first part of this two-part series considered differences between silicone-hydrogel (SiH) contact lenses in terms of their effect on ocular parameters known to be influenced by oxygen levels. Oxygen transmissibility (Dk/t) differences between lenses within this category appear to have little impact on such clinical outcomes. Here, we will consider clinical performance attributes that are known to vary between lens types and highlight the properties that are indeed important considerations in achieving an optimal clinical lens-wearing experience.

Non-oxygen related effects

The following is a list of adverse events that may occur with contact lens wear but either have been shown to be independent of oxygenation or have a converse relation with Dk/t in SiH lenses.

Infection

SiH contact lenses and their high oxygen delivery were introduced with the prospect of reducing the risk of severe keratitis, most commonly associated with microbial infection, to levels associated with daily wear (DW) of hydrogel lenses. Unfortunately the lenses did not deliver on the promise.[1-4] Recent epidemiological studies continue to find closed eye wear as the major risk factor for infection, with other identified risk factors including contact lens type, full-time wear, correction for hypermetropia or to alter eye colour, internet purchase of contact lenses, failure to wash hands before cleaning, poor storage case hygiene, younger age group, male gender, smoking, season, climatic conditions, less than six months' wear experience, and higher socioeconomic class.[3-6] There is some suggestion that severity of the keratitis and the risk of vision loss is linked to Dk/t[1-3,7] but certainly no evidence of an effect within the SiH category, even where differences between lens brands among different modalities were found.[4]

TABLE 1

Presence or absence of differences for the given performance attributes between different lens types

Performance attribute	Daily wear		Continuous wear	
	Hydrogel vs SiH	SiH vs SiH	Hydrogel vs SiH	SiH vs SiH
Oxygen related				
Microcysts	no	no	yes	no
Endothelial blebs	yes	no	yes	no
Polymegethism	yes	no	yes	no
Vascularisation	yes	no	yes	no
Limbal redness	yes	no	yes	no
Non-oxygen related				
Infection	no	no	no	no
Inflammation	yes	no	yes	no
Corneal staining	yes	yes	yes	yes
CLPC	yes	yes	yes	yes
Conjunctival splits	yes	yes	yes	yes
SEALS	yes	yes	yes	yes
Mucin balls	yes	yes	yes	yes
Comfort	yes	yes	yes	yes

Inflammation

Non-infectious infiltrative keratitis is an important inflammatory condition that can lead to discomfort, scarring and lens intolerance. There is no suggestion that increasing oxygen transmissibility leads to a reduction of risk of infiltrative keratitis; indeed, there is evidence to suggest that continuous wear (CW) of SiH lenses is associated with equal, if not greater risk, of infiltrates than hydrogels.[1,8] This is unlikely to be related to Dk/t per se and may be more related to duration of contact lens wear, surface properties of the material or other aspects of the methodology of the study reporting this finding. The implication with respect to the topic of this article is that there are important material or additional predisposing factors other than Dk/t to take into consideration.

Corneal staining

Corneal staining occurs during wear of both hydrogel and SiH lenses. Recently there has been a keen interest in differential staining patterns with SiH lenses dependent on the contact lens care and storage solution.[9] Links between staining and Dk/t are tenuous at best. Certainly six hours of anoxia does not lead to corneal staining.[10]

Papillary conjunctivitis

Contact lens related papillary conjunctivitis is a principal cause of contact lens intolerance, particularly in association with CW.[11,12] Although the mechanism remains poorly understood, it is thought that the major factors involved are mechanical trauma of the upper palpebral conjunctiva and immunologic and inflammatory mechanisms.[11] As such, material ▶

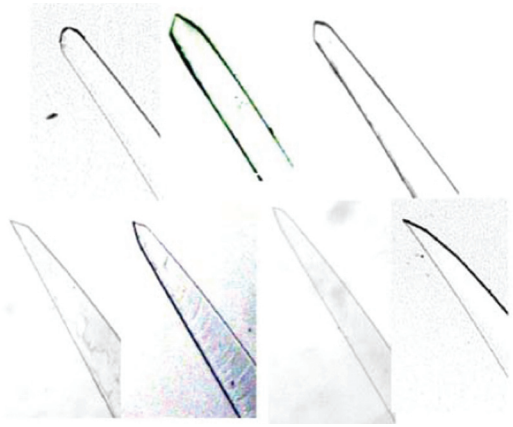

Figure 1 Series of photomicrographs of slivers of a range of commercially available lenses showing vastly different edge design philosophies

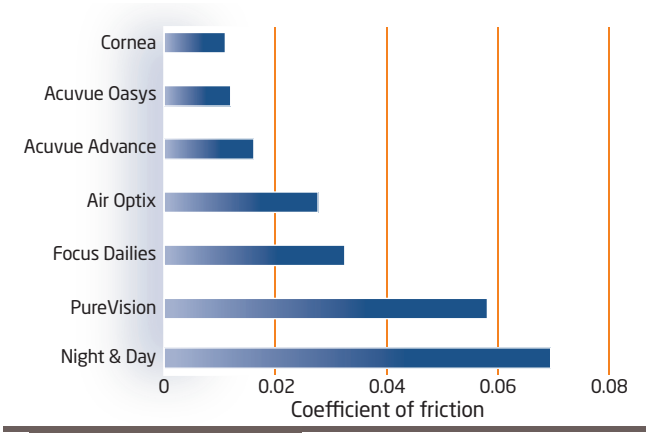

Figure 2 Coefficients of friction of select SiH and hydrogel lenses, redrawn from Ross *et al*[28]

modulus, lens surface characteristics and lens design are implicated as the contact lens related causative factors.

Conjunctival splits

Lofstrom and Kruse recently identified a new finding arising from the use of SiH contact lenses.[13] In certain patients, conjunctival splits and fringes have been observed near to where the edge of the contact lens sits. For the most part, the subjects appear to be symptomless and there do not appear to be serious ramifications. Mechanical effects are most likely the cause as CW causes a greater effect than DW.[14] Material modulus and lens design are implicated as the lens related causative factors.

SEALs

Superior epithelial arcuate lesions (SEALs) are an infrequent occurrence of lens wear that give rise to concern as they present a consistent breach in the corneal epithelial surface. They may occur more commonly with SiH lenses. It is currently thought that SEALs are produced by mechanical chaffing as a result of inward pressure of the upper lid, in an area where the peripheral corneal topography and lens design, rigidity, and surface characteristics combine to create excessive 'frictional' pressure and abrasive shear force on the epithelial surface.[15]

Mucin balls

Mucin balls are small spheroidal structures that are visible beneath the surface of a contact lens and seem to occur with greater frequency with SiH lenses used for CW. While they are generally considered of limited clinical consequence, they can become inclusion bodies within the corneal epithelium.[16] Aside from patient factors involved in their development, lens modulus, design and surface properties appear to be key aetiological factors.[17]

Refractive error

Unwanted orthokeratology effects have been noticed during wear of SiH lenses, particularly those of high power.[18] Lenses with higher modulus and a flatter back optic zone radius than the cornea are likely to lead to this effect by compressing and thus flattening the central cornea. This effect may act in the opposite manner to the myopic creep effect reported with hydrogel lenses.

Discomfort

Of the factors that govern success in contact lens wear, comfort is the most important.[19,20] A number of articles have recently appeared suggesting the use of SiH lenses leads to greater comfort than is achieved with hydrogels.[21-24] Despite the apparent consistency between the studies, the position remains debatable. The typical design of these studies has been to switch hydrogel lens wearers to SiH lenses. However, the absence of a masked control group means that the reports of increased comfort may arise from a number of possible biases. Importantly, none of these papers makes a conclusive link to oxygen levels beneath a contact lens and such a link is most unlikely. In truth, there may be a false sense of comfort when oxygen levels are low, since hypoxia has been shown to induce corneal hypoesthesia.[25] Our research suggests that some hydrogel lenses are more comfortable than some SiH lenses.[26] Material modulus, lens design and surface properties such as lubricity are the principal determinants of comfort and there will be differences in comfort levels between SiH lenses as there are when comparing hydrogel lenses. Any possible relation between comfort and oxygen levels is far outweighed by these other lens properties.

Negative effects of higher Dk/t

Table 1 compares differences between hydrogel and SiH lenses, and within the SiH group, across a range of oxygen and non-oxygen related performance attributes from clinical studies and current beliefs. In addition to the absence of effects within the SiH group in terms of oxygen related properties, there is a range of possible negative effects associated with higher Dk/t values. It is important to emphasise that these are not a direct effect of higher oxygenation but as a consequence of the material properties necessary to achieve high Dk.

Material Dk is generally a function of the proportions of silicone, water and oxygen-impermeable components. In turn the proportion of silicone will tend to be proportional to modulus of the material. While it was initially thought that a higher modulus might produce beneficial effects from greater tear exchange, it has become apparent that it is associated with numerous negative consequences. From the list above, it seems that through its association with higher lens modulus, higher Dk/t may be associated with increased frequency of CLPC, conjunctival splits, SEALs, mucin balls, refractive error changes and discomfort.

Important SiH lens brand differences unrelated to Dk/t

As demonstrated from the above discussion there are many lens parameters that will influence the clinical performance of a contact lens. Aside from modulus, lens design seems to play a key role in development of CLPC, conjunctival splits, SEALs, and discomfort. Figure 1 shows a set of ▶

commercially available lens edge profiles. Thinner lens edges can lead to more comfortable lenses, but may also result in less movement and conjunctival staining. Chisel shape edges may be responsible in part with lens modulus for producing effects such as conjunctival splits and discomfort.[13]

Quality of the lens surface is also implicated in many adverse events with silicone-hydrogel lenses. Accumulation of material at the surface may lead to immunological and infective consequences.[27] A high coefficient of friction may be associated with discomfort and mechanical type effects such as papillary conjunctivitis and SEALs. Lens brands using Hydraclear technology seem to have the lowest coefficient of friction and this is thought to provide these lenses with a slippery feel and greater comfort (Figure 2).[28] Some authors report that this benefit may be short-term,[29] but when appropriate analytical methods are used, clinically and statistically significant end-of-day comfort benefits over the duration of wear are obvious.[30] Further examples of differences between lenses include water content, susceptibility to dehydration and incorporation of ultraviolet blocker.

Out in the great laboratory that is the real world, there appears to be practical recognition of the points raised in this article. First, the lens with the lowest Dk/t of available SiH materials is one of the largest selling SiH brands in the world. There are no reports of which we are aware that suggest that this lens produces hypoxic problems. Second, the first SiH lens introduced to the market remains the lens with the highest Dk/t; manufacturers have not seen fit to pursue lenses with greater Dk/t due presumably to a lack of hypoxic problems with lenses at lower Dk/t values and to avoid the unwanted, attendant problems arising from the higher silicone contents required.

Conclusion

Part one of this series demonstrated that there is no need to strive for the highest Dk/t possible when prescribing SiH lenses. In contrast, there is actually reason to select lower Dk materials within the SiH category, as material modulus, which is generally proportional to Dk/t, is thought to be associated with CLPC, conjunctival splits, comfort, unwanted orthokeratology, SEALs and mucin ball development. Other brand dependent lens properties that are largely unrelated to Dk/t, such as surface properties and lens design, will also affect corneal staining, CLPC, conjunctival splits, comfort, SEALs and mucin ball development. Theoretically, prescribing contact lenses with the highest possible Dk/t is a fine concept but only where other aspects of lens behaviour match. In reality, different lens brands behave quite differently. Practically the greatest clinical success with SiH lenses will be achieved by closely considering the range of parameters of available lenses and basing the selection on everything but Dk/t.

This article was originally published in Optician, 2009, Vol 238, No 6218, 26-30.

Professor Noel Brennan is general manager of Brennan Consultants in Melbourne Australia and adjunct professor at Queensland University of Technology. **Dr Philip Morgan** is a senior lecturer in optometry, and is director of Eurolens Research, at the University of Manchester

References Part 1

1. Brennan N. Corneal oxygenation during contact lens wear: comparison of diffusion and EOP-based flux models. Clin Exp Optom 2005; 88:103-108.

2. Brennan N. Beyond flux: total corneal oxygen consumption as an index of corneal oxygenation during contact lens wear. Optom Vis Sci 2005; 82:467-472.

3. Brennan NA. A model of oxygen flux through contact lenses. Cornea 2001; 20:104-108.

4. Compan V, Lopez-Alemany A, Riande E, et al. Biological oxygen apparent transmissibility of hydrogel contact lenses with and without organosilicon moieties. Biomat 2004; 25:359-365.

5. Huang P, Zwang-Weissman J, Weissman BA. Is contact lens "T" still important? Contact Lens Ant Eye 2004; 27:9-14.

6. Radke CJ, Chhabra M. Minimum Contact Lens Oxygen Transmissibility (Dk/L) With Monod Kinetics for the Corneal Oxygen Consumption Rate. Invest. Ophthalmol. Vis. Sci. 2005; 46:904-.

7. Fonn D, Bruce A. A review of the Holden-Mertz criteria for critical oxygen transmission. Eye Contact Lens 2005; 31:247-251.

8. Fonn D, Sweeney D, Holden B, et al. Corneal oxygen deficiency. Eye Contact Lens 2005; 31:23-27.

9. Holden BA, Stretton S, Lazon de la Jara P, et al. The future of contact lenses: Dk really matters. Contact Lens Spectrum 2006; 21:20-28.

10. Bonanno JA, Clark C, Pruitt J, et al. Tear oxygen tension under silicone-hydrogel lenses in human subjects. Invest Ophthalmol Vis Sci 2008; 49:E-abstract 4846.

11. Fatt I. New physiological paradigms to assess the effect of lens oxygen transmissibility on corneal health. CLAOJ 1996; 22:25-29.

12. Fatt I, Freeman RD, Lin D. Oxygen tension distributions in the cornea: a re-examination. Exp Eye Res 1974; 18:357-365.

13. Bruce AS. Local oxygen transmissibility of disposable contact lenses. Contact Lens Anterior Eye 2003; 26:189-196.

14. Efron N, Morgan PB, Cameron ID, et al. Oxygen permeability and water content of silicone hydrogel contact lens materials. Optom Vis Sci 2007; 84:328-337.

15. Brennan N. Corneal oxygen consumption beneath toric soft lenses. 2008:In preparation.

16. Leibowitz H, Laing R, Sandstrom M. Continuous wear of hydrophilic contact lenses. Arch Ophthalmol 1973; 89:306-310.

17. Sarver MD, Staroba JE. Corneal edema with contact lenses under closed-eye conditions. AmJ Optom Physiol Opt 1978; 55:739-743.

18. Binder P. Complications associated with extended wear of soft contact lenses. Ophthalmol 1979; 86:1093-1101.

19. Holden B, Sweeney D, Swarbrick H, et al. The vascular response to long-term extended contact lens wear. Clin Exp Optom 1986; 69:112-119.

20. Zantos S, Holden B. Transient endothelial changes soon after wearing soft contact lenses. Am J Optom Physiol Opt 1977; 54:856-858.

21. Zantos S, Holden B. Ocular changes associated with continuous wear of contact lenses. Aust J Optom 1978; 61:418-426.

22. Zantos S. Cystic formations in the corneal epithelium during extended wear of contact lenses. Int Contact Lens Clin 1983; 10:128-146.

23. Holden B, Sweeney D, Vannas A, et al. Effects of long-term extended contact lens wear on the human cornea. Invest Ophthalmol Vis Sci 1985; 26:1489-1501.

24. Schoessler J. Corneal endothelial polymegathism associated with extended wear. Int Contact Lens Clin 1983; 10:148-156.

25. Dumbleton KA, Chalmers RL, Richter DB, et al. Changes in myopic refractive error with nine months' extended wear of hydrogel lenses with high and low oxygen permeability. Optom Vis Sci 1999; 76:845-849.

26. Ruben M, Brown N, Lobascher D, et al. Clinical manifestations secondary to soft contact lens wear. Br J Ophthalmol 1976; 60:529-531.

27. McM nnies CW, Chapman-Davies A, Holden BA. The vascular response to contact lens wear. Am J Optom Physiol Opt 1982; 59:795-799.

28. MacRae S, Matsuda M, Shelland S, et al. The effects of hard and soft contact lenses on the endothelium. Am J Ophthalmol 1986; 102:50-57.

29. Farris R, Donn A. Corneal respiration with soft contact lenses. J Am Optom Assoc 1972; 43:292-294.

30. Roth HW. The etiology of ocular irritation in soft lens wearers: distribution in a large clinical sample. Contact Intraoc Lens Med J 1978; 4:38.

31. McMonnies C. Contact lens-induced corneal vascularization. Int Contact Lens Clin 1983; 10:12-21.

32. Efron N. Vascular response of the cornea to contact lens wear. J Am Optom Assoc 1987; 58:836-846.

33. Holden B, Sweeney D, Sanderson G. The minimum precorneal oxygen tension to avoid corneal oedema. Invest Ophthalmol Vis Sci 1984; 25:476-480.

34. Polse K, Mandell R. Critical oxygen tension at the corneal surface. Arch Ophthalmol 1971; 84:505-508.

35. Holden B, Mertz G. Critical oxygen levels to avoid corneal edema for daily and extended wear contact lenses. Invest Ophthalmol Vis Sci 1984; 25:1161-1167.

36. La Hood D, Grant T. Striae and folds as indicators of corneal œdema. Optom Vis Sci 1990; 67 (suppl.):196.

37. Morgan PB, Maldonado-Codina C, Quhill W, et al. Central and peripheral oxygen transmissibility thresholds to avoid corneal swelling during open eye soft contact lens wear.J Biomed Mat Res 2008:Submitted for publication.

38. Brennan NA, Fonn D, Corneal hypoxia, in Silicone-hydrogels: continuous wear contact lenses, D.F. Sweeney, Editor. 2004, Butterworth-Heinemann: London.

39. Cox I, Zantos S, Orsborn G. The overnight corneal swelling response of non-wear, daily wear, and extended wear soft lens patients. Int Contact Lens Clin 1990; 17:134-137.

40. Brennan NA, Coles M-LC, Continuous wear, in Contact Lens Practice, N. Efron, Editor. 2002, Butterworrth-Heinemann: Oxford. p. 275-294.

41. Fonn D, du Toit R, Simpson TL, et al. Sympathetic swelling response of the control eye to soft lenses in the other eye. Invest Ophthalmol Vis Sci 1999; 40:3116-3121.

42. Holden BA, Grant T, Kotow M, et al. Epithelial microcysts with daily and extended wear of hydrogel and rigid gas permeable contact lenses. . Invest Ophthalmol Vis Sci 1987; 28(Suppl):372.

43. Hickson S, Papas E. Prevalence of idiopathic corneal anomalies in a non contact lens-wearing population. Optom Vis Sci 1997; 74:293-297.

44. Holden BA, Sweeney DF. The significance of the microcyst response: a review. Optom Vis Sci 1991; 68:703-707.

45. Sweeney DF, Keay L, Jalbert I, et al., Clinical performance of silicone hydrogel lenses, in Silicone hydrogels: the rebirth of continuous wear contact lenses, D.F. Sweeney, Editor. 2000, Butterworth-Heinemann:

Oxford. p. 90-149.
46. Brennan NA, Coles ML, Connor HR, et al. A 12-month prospective clinical trial of comfilcon A silicone-hydrogel contact lenses worn on a 30-day continuous wear basis. Cont Lens Anterior Eye 2007; 30:108-118.
47. Dumbleton KA, Chalmers RL, Richter DB, et al. Vascular response to extended wear of hydrogel lenses with high and low oxygen permeability. Optom Vis Sci 2001; 78:147-151.
48. Brennan NA, Coles M-LC, Levy B, et al. One-Year Prospective Clinical Trial of balafilcon A (PureVision) Silicone-hydrogel Contact Lenses Used on a 30-Day Continuous Wear Schedule. Ophthalmol 2002; 109:1172-1177.
49. Santodomingo-Rubido J, Wolffsohn JS, Gilmartin B. Changes in ocular physiology, tear film characteristics, and symptomatology with 18 months silicone hydrogel contact lens wear. Optom Vis Sci 2006; 83:73-81.
50. Santodomingo-Rubido J, Wolffsohn JS, Gilmartin B. Adverse events and discontinuations during 18 months of silicone hydrogel contact lens wear. Eye Contact Lens 2007; 33:288-292.
51. Papas E. On the relationship between soft contact lens oxygen transmissibility and induced limbal hyperaemia. Exp Eye Res 1998; 67:125-131.
52. Brennan NA, Coles ML, Ang JH. An evaluation of silicone-hydrogel lenses worn on a daily wear basis. Clin Exp Optom 2006; 89:18-25.
53. Guillon M, Maissa C. The effect of optimising silicone hydrogels key physical properties on extended wear clinical performance. Invest Ophthalmol Vis Sci 2006; 49:ARVO E-abstract 2382.
54. Maldonado-Codina C, Morgan PB, Schnider CM, et al. Short-term physiological response in neophyte subjects fitted with hydrogel and silicone-hydrogel contact lenses. Optom Vis Sci 2004; 81:911-921.
55. Morgan PB, Efron N. Comparative clinical performance of two silicone hydrogel contact lenses for continuous wear. Clin Exp Optom 2002; 85:183-192.
56. Papas E, Willcox MDP. Reducing the consequences of hypoxia: the ocular redness response. Contact Lens Spectrum 2006; 21 (suppl.):32-37.
57. Inagaki Y, Akahori A, Sugimoto K, et al. Comparison of corneal endothelial bleb formation and disappearance processes between rigid gas-permeable and soft contact lenses in three classes of dk/l. Eye Contact Lens 2003; 29:234-237.
58. Brennan NA, Coles M-LC, Connor RM, et al. Short-term corneal endothelial response to wear of silicone-hydrogel contact lenses in east asian eyes. Eye Contact Lens 2008; 34:317-321.
59. Chang SW, Hu FR, Lin LL. Effects of contact lenses on corneal endothelium -a morphological and functional study. Ophthalmologica 2001; 215:197-203.
60. Yamauchi K, Hirst LW, Enger C, et al. Specular microscopy of hard contact lens wearers II. Ophthalmology 1989; 96:1176-1179.
61. Carlson KH, Bourne WM. Endothelial morphologic features and function after long-term extended wear of contact lenses. Arch Ophthalmol 1988; 106:1677-1679.
62. Stocker EG, Schoessler JP. Corneal endothelial polymegathism induced by PMMA contact lens wear. Invest Ophthalmol Vis Sci 1985; 26:857-863.
63. Schoessler JP, Barr JT, Freson DR. Corneal endothelial observations of silicone elastomer contact lens wearers. Int Contact Lens Clin 1984; 11:337.
64. Liu Z, Pflugfelder SC. The effects of long-term contact lens wear on corneal thickness, curvature, and surface regularity. Ophthalmology 2000; 107:105-111.
65. Myrowitz EH, Melia M, O'Brien TP. The relationship between long-term contact lens wear and corneal thickness. Clao J 2002; 28:217-220.
66. Alharbi A, Swarbrick HA. The effects of overnight orthokeratology lens wear on corneal thickness. Invest Ophthalmol Vis Sci 2003; 44:2518-2523.
67. Binder P. Myopic extended wear with the Hydrocurve II soft contact lens. Ophthalmol 1983; 90:623-626.
68. Harris MG, Sarver MD, Polse KA. Corneal curvature and refractive error changes associated with wearing hydrogel contact lenses. Am J Optom Physiol Opt 1975; 52:313-319.
69. Fonn D, MacDonald KE, Richter D, et al. The ocular response to extended wear of a high Dk silicone hydrogel contact lens. Clin Exp Optom 2002; 85:176-182.
70. Patel S. Changes in myopic refractive error with nine months' extended wear of hydrogel lenses with high and low oxygen permeability. Optom Vis Sci 2000; 77:285.
71. Smith EL, Greeman P, Ho A, et al. Methods and apparatuses for altering relative curvature of field and positions of peripheral off-axis focal positions. US patent 7025460 2006.
72. Szczotka-Flynn LB. Unintended Ortho-k Effects From Silicone Hydrogel Lenses. Contact Lens Spectrum 2004; 19(8):19-20.

References Part 2

1. Morgan PB, Efron N, Hill EA, et al. Incidence of keratitis of varying severity among contact lens wearers. Br J Ophthalmol 2005; 89:430-436.
2. Schein OD, McNally JJ, Katz J, et al. The incidence of microbial keratitis among wearers of a 30-day silicone hydrogel extended-wear contact lens. Ophthalmology 2005; 112:2172-217
3. Stapleton F, Keay L, Edwards K, et al. The Incidence of contact lens-related microbial keratitis in Australia. Ophthalmology 2008; 115:1655-1662.
4. Dart JK, Radford CF, Minassian D, et al. Risk factors for microbial keratitis with contemporary contact lenses: a case-control study. Ophthalmology 2008; 115:1647-1654.
5. Morgan PB, Efron N, Brennan NA, et al. Risk factors for the development of corneal infiltrative events associated with contact lens wear. Invest Ophthalmol Vis Sci 2005; 46:31363143.
6. Stapleton F, Keay LJ, Sanfilippo PG, et al. Relationship between climate, disease severity, and causative organism for contact lens-associated microbial keratitis in Australia. AmJ Ophthalmol 2007; 144:690-698.
7. Keay L, Edwards K, Naduvilath T, et al. Factors affecting the morbidity of contact lens-related microbial keratitis: a population study. Invest Ophthalmol Vis Sci 2006; 47:4302-4308.
8. Szczotka-Flynn L, Diaz M. Risk of corneal inflammatory events with silicone hydrogel and low dk hydrogel extended contact lens wear: a meta-analysis. Optom Vis Sci 2007; 84:247-256.
9. Andrasko G, Ryen K. Corneal staining and comfort observed with traditional and silicone hydrogel lenses and multipurpose solution combinations. Optometry 2008; 79:444-454.
10. O'Leary DJ, Wilson G, Henson DB. The effect of anoxia on the human corneal epithelium. Am J Optom Physiol Opt 1981; 58:472-476.
11. Skotnitsky CC, Naduvilath TJ, Sweeney DF, et al. Two presentations of contact lens-induced papillary conjunctivitis (CLPC) in hydrogel lens wear: local and general. Optom Vis Sci 2006; 83:27-36.
12. Spring TF. Reaction to hydrophilic lenses. Med J Aust 1974; 1:449-450.
13. Lofstrom T, Kruse A. A Conjunctival Response to Silicone Hydrogel Lens Wear: A new finding reveals how silicone hydrogel lenses may affect the conjunctival epithelium. Contact Lens Spectrum 2005; 20(9):42-45.
14. Santodomingo-Rubido J, Wolffsohn J, Gilmartin B. Conjunctival epithelial flaps with 18 months of silicone hydrogel contact lens wear. Eye Contact Lens 2008; 34:35-38.
15. Holden BA, Stephenson A, Stretton S, et al. Superior epithelial arcuate lesions with soft contact lens wear. Optom Vis Sci 2001; 78:9-12.
16. Pritchard N, Jones L, Dumbleton K, et al. Epithelial inclusions in association with mucin ball development in high-oxygen permeability hydrogel lenses. Optom Vis Sci 2000; 77:68-72.
17. Tan J, Keay L, Jalbert I, et al. Mucin balls with wear of conventional and silicone hydrogel contact lenses. Optom Vis Sci 2003; 80:291-297.
18. Szczotka-Flynn LB. Unintended Ortho-k Effects From Silicone Hydrogel Lenses. Contact Lens Spectrum 2004; 19(8):19-20.
19. Pritchard N, Fonn D, Brazeau D. Discontinuation of contact lens wear: a survey. Int Contact Lens Clin 1999; 26:157-162.
20. Young G, Veys J, Pritchard N, et al. A multi-centre study of lapsed contact lens wearers. Ophthalmic Physiol Opt 2002; 22:516-527.
21. Dillehay SM, Miller MB. Performance of Lotrafilcon B silicone hydrogel contact lenses in experienced low-Dk/t daily lens wearers. Eye Contact Lens 2007; 33:272-277.
22. Dumbleton K, Keir N, Moezzi A, et al. Objective and subjective responses in patients refitted to daily-wear silicone hydrogel contact lenses. Optom Vis Sci 2006; 83:758-768.
23. Long B, McNally J. The clinical performance of a silicone hydrogel lens for daily wear in an Asian population. Eye Contact Lens 2006; 32:65-71.
24. Riley C, Young G, Chalmers R. Prevalence of ocular surface symptoms, signs, and uncomfortable hours of wear in contact lens wearers: the effect of refitting with daily-wear silicone hydrogel lenses (senofilcon a). Eye Contact Lens 2006; 32:281-286.
25. Millodot M, O'Leary DJ. Effect of oxygen deprivation on corneal sensitivity. Acta Ophthalmol (Copenh) 1980; 58:434-439.
26. Brennan NA, Coles M-LC, Connor HR, et al. Silicone hydrogel contact lens comfort. Optom Vis Sci 2007; 84:e-abstract 070037.
27. Brennan NA, Coles M-LC. Deposits and symptomatology with soft contact lens wear. Int Contact Lens Clin 2000; 27:75-100.
28. Ross G, Nasso M, Franklin V, et al. Silicone hydrogels: Trends in products and properties. Ophthalmic Res 2005; 2005:27&162.
29. Dumbleton KA, Woods CA, Jones LW, et al. Comfort and adaptation to silicone hydrogel lenses for daily wear. Eye Contact Lens 2008; 34:215-223.
30. Brennan NA, Coles M-LC, Connor HRM, et al. Silicone hydrgel contact lens comfort. Optom Vis Sci 2007; 84:E-abstract 070037.