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A decade with silicone hydrogels: Part 1

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Introduction

The last decade has been incredibly significant for the development of contact lens (CL) materials. The launch of the first silicone hydrogels (SiHs) in the late 1990's represented a major milestone in CL material science. The drive behind the evolution of CL materials was related to the need to enhance patient comfort and vision, whilst improving biocompatibility and minimising the impact of the material on corneal physiology. Hydrogel CLs offer a material that has good wettability, vision and initial patient comfort. However, despite many advances in hydrogel material properties, there has always been a limit to the level of oxygen available to the cornea. In addition, patient symptoms such as discomfort and end of day dryness continue to be a problem. SiHs combine the initial comfort of a soft lens material with substantial improvements in oxygen performance. There is also growing evidence to support the fact that some SiHs can offer increased comfortable wearing time, with reduced symptoms of end of day dryness. This has resulted in changing attitudes to clinician's contact lens prescribing habits and continued growth of the SiH market.

The first SiH lenses allowed sufficient oxygen transmissibility to meet corneal oxygen needs during overnight wear (ON).[1,2] However, continuous wear (CW, or ON wear for up to 30 nights) has not proved as popular as predicted, particularly in the UK and other European markets;[3] this modality currently accounts for only 7% of new fits and 13% of refits in the UK.[4] This less than expected growth is almost certainly due to caution on the part of the practitioner, bearing in mind that the risk of corneal inflammatory events and microbial keratitis remain higher when patients sleep in their lenses, both historically[5-7] and with modern materials,[8,9] although consumer reluctance to embrace this modality may also be a factor.

As SiH lenses started to establish themselves within the market, it became clear that the properties of these materials offered benefits for wearers over and above their use for ON wear. Oxygen performance is beneficial to any patient who wears lenses for long hours, or for those with higher or more complex prescriptions and hence thicker lenses. Consequently, the materials started to find a place as ideal lenses for refitting daily wear (DW) patients with signs of hypoxia, and also as first choice for many new DW fits. Increased interest was generated in the use of SiH materials for more "routine" DW fits and at the same time efforts were being made by manufacturers to address some of the limitations of the first SiH materials, by finding an optimum balance of oxygen delivery, mechanical performance and wettability. From 2004 there has been a steady increase in the number of SiH lenses available, with these newer materials primarily aimed at DW or occasional overnight use. *Tables 1-3* summarise SiH lenses currently available in the UK and their key features.

This two-part review of currently available SiHs and the many benefits they offer patients will look at data generated over the past 10 years for a number of factors relating to SiH materials and lens wear. Part 1 of this review will explore the potential oxygen and comfort benefits of SiH materials, along with their differences in wettability and UV transmission from traditional, polyHEMA-based materials.

Table 1: Frequent replacement and daily disposable SiH spherical lenses in the UK

Brand name	PureVision®	AIR OPTIX™ NIGHT & DAY®	AIR OPTIX™	AIR OPTIX™ AQUA	ACUVUE® ADVANCE®	ACUVUE OASYS®	1•DAY ACUVUE® TruEye™	Biofinity™	PremiO
Material	Balafilcon A	Lotrafilcon A	Lotrafilcon B		Galyfilcon A	Senofilcon A	Narafilcon A	Comfilcon A	Asmofilcon A
Manufacturer	Bausch & Lomb	CIBA Vision			Johnson & Johnson Vision Care Companies			CooperVision	Menicon
Replacement frequency; modality	1/12; DW or up to 30N CW		1/12; DW or up to 6N EW		2/52; DW	2/52; DW 1/52; up to 6N EW	Single use; DW 1-day replacement	1/12; DW or up to 30N CW	2/52; DW 1/52; up to 6N EW
Surface treatment	Plasma oxidation	Plasma coating			None			None	Nanogloss™ surface coating
Wetting agent	None			Moisture agent	Internal via - HYDRACLEAR® Technology	Internal via - HYDRACLEAR® *Plus* Technology	Internal via - HYDRACLEAR® 1 Technology	None	
Oxygen permeability (x10^{-11})	91	140	110	110	60	103	100	128	129
Oxygen transmissibility (10^{-9}, -3.00D)	101	175	138	138	86	147	118	160	161
Modulus (MPa)	1.1	1.4	1.0	1.0	0.43	0.72	0.66	0.75	0.9
Water content (%)	36	24	33	33	47	38	46	48	40
UV blocking	No				Class 1			No	
Power range	+6.00D to -12.00D	+6.00D to -10.00D			+8.00D to -12.00D		-0.50D to -6.00D (other BVPs later)	+6.00D to -10.00D	+6.00D to -13.00D
BOZR (mm)	8.3, 8.6	8.4, 8.6	8.6		8.3, 8.7	8.4, 8.8	8.5 (9.0 later)	8.6	8.3, 8.6
Diameter (mm)	14.0	13.8	14.2		14.0	14.0	14.2	14.0	14.0

Table 2: Frequent replacement SiH toric and multifocal lenses (ACLM CL Yearbook 2008)

Brand name	PureVision® Toric	ACUVUE® ADVANCE® for ASTIGMATISM	AIR OPTIX™ for Astigmatism	PureVision® Multifocal
Material	Balafilcon A	Galyfilcon A	Lotrafilcon B	Balafilcon A
Manufacturer	Bausch & Lomb	Johnson & Johnson Vision Care Companies	CIBA Vision	Bausch & Lomb
Replacement frequency & modality	1/12 DW 30N CW	2/52 DW	1/12 DW 30N CW	1/12 DW 30N CW
Prescription range	Sph: +6.00 to –9.00 Cyls: –0.75 to –2.25 in 0.50 steps Axes: 10° to 180° in 10° steps	Sph: +6.00 to –9.00 Cyls: –0.75 to –2.25 in 0.50 steps Axes: 10° to 180° in 10° steps	Sph: 0.00 to –6.00 Cyls: –0.75 to –1.75 in 0.50 steps Axes: 10° to 180° in 10° steps	Sph: +6.00 to –10.00 Add: low (up to +1.50) or high

Clinical performance of SiHs

Oxygen performance

Unlike conventional hydrogel materials where the oxygen performance is related to, and limited by, the water content,[10] the way in which oxygen is transported through silicone hydrogels is different and is not dependent on water content alone.[11] In SiHs, the oxygen is transmitted mainly through the silicone-based component of the lens material, which allows vast improvements in oxygen performance to be obtained compared to hydrogel materials.[11,12]

Figure 1: Relationship between water content and oxygen permeability of SiH materials

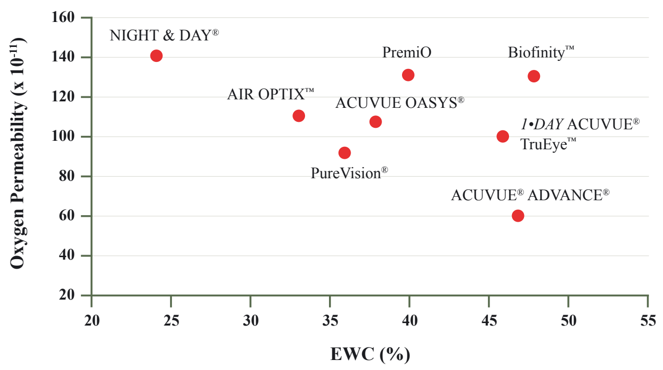


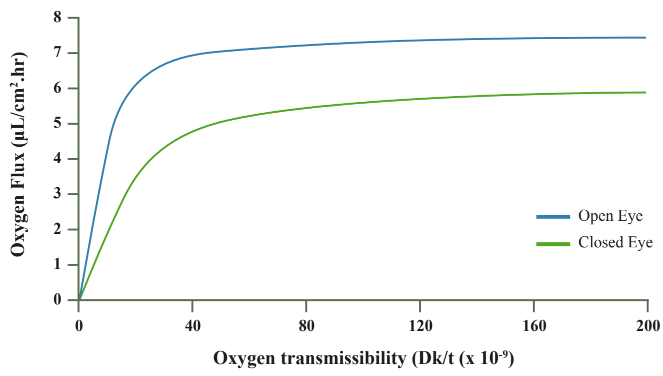
Figure 1 shows the relationship between water content and oxygen permeability (Dk) for SiH materials. Below 50% water content, the material Dk is dependent on the structure of the material itself. Oxygen is more soluble in the silicone material than in the water so as the ratio of the material to water increases (i.e. water content decreases), the Dk increases. By decoupling the water content and the Dk, there is no longer a situation where increasing the water content of the material increases the Dk, as is the case with conventional hydrogel materials. It is interesting to note that two newer SiH materials (comfilcon A and asmofilcon A) have higher than expected Dk's for their water content. According to the manufacturers, this is due to the chemistry used in the lens' manufacture where long chain silicone-containing macromers allow more efficient oxygen transport and thus less silicone is needed to give the desired permeability. All SiH lenses provide a significant increase in oxygen supply to the cornea compared to hydrogel lenses,[12] with all easily able to meet the challenge of the Holden and Mertz criteria for daily wear.[13,14] Similarly SiH lenses that are indicated for overnight wear are able to meet the criteria for closed eye conditions, limiting overnight swelling to levels seen with no lens wear.[13,14]

Oxygen flux

Traditionally, the oxygen performance of a material or a contact lens has been described in terms of its oxygen permeability (Dk) or oxygen transmissibility (Dk/t).[10] These values give useful comparative data as to the ease with which oxygen can pass through a material or lens of a given thickness. In a clinical situation however it may be more useful to consider the amount of oxygen that passes through a lens per unit time whilst on the cornea. This value is known as the oxygen flux.[15-17]

The advantage of using oxygen flux is that it takes into account the difference in oxygen tension (or concentration) across the lens. This oxygen tension difference acts as a driving force for oxygen to move through the lens. The oxygen tension at the front of the lens is taken to be a constant 159mmHg for open eye conditions and 59mmHg for closed eye conditions.[18] The oxygen tension at the posterior lens surface depends on the lens transmissibility. The greater the difference between the two, the greater the driving force encouraging oxygen to pass through the lens.

Figure 2: Relationship between oxygen flux and transmissibility of SiH materials



As shown in *Figure 2*, at lower oxygen transmissibility values, there is clearly a relationship between oxygen flux and transmissibility such that the greater the transmissibility, the greater the oxygen flux. However, there is a maximum reached where the oxygen tension at the posterior surface of the lens matches the oxygen tension at the anterior surface and there is no longer any driving force for further oxygen to pass through the lens. In practical terms, this means that for lower values of oxygen transmissibility, an increase in transmissibility will correspond to a similar increase in oxygen flux with, for example, an increase in Dk/t from 10 to 30 units resulting in approximately three times more oxygen being made available to the cornea. However, as higher transmissibility values are considered, such as those associated with SiHs, there is a much smaller relative increase in oxygen flux.[17] Even if materials with significantly higher transmissibilities than those currently available are produced, they will only result in a relatively small increase in oxygen being made available to the cornea. This is best illustrated in *Figure 2*. For example, senofilcon A has a central oxygen flux percentage of 98 per cent in open eye conditions and 96 per cent for closed eye conditions. This means that the lens makes available 98 per cent of the oxygen to the central cornea compared with no lens for daily wear and 96 per cent for overnight wear, which is comparable with other SiHs with a range of oxygen transmissibilities.

Many papers have been published in peer-reviewed journals highlighting the oxygen performance benefits of SiHs. Corneal swelling associated with SiH lens wear, even on an overnight basis, is similar to wearing no lens at all.[19-24] It is very rare to see severe hypoxic complications such as striae, folds and microcysts. [1,2,25-28] Chronic limbal hyperaemia, which is a feature of many soft CL wearers, was noted to decrease significantly with SiH materials on an ON basis.[29-38] More recently, studies have shown that SiHs worn on a DW basis also reduce limbal hyperaemia.[39-45] Refitting existing wearers who have corneal neovascularisation has been shown to allow remarkably rapid resolution of the condition[29,30,41,42,46-48] to leave only ghost vessels. Other studies have also shown reduced bacterial binding and epithelial mitoses in patients wearing highly permeable SiH lenses.[49-56]

Blebs are an acute endothelial response to hypoxia and can therefore be considered a sensitive index of lens material's oxygen delivery.[57,58] A recent study compared the bleb response associated with SiH lenses to that seen with conventional hydrogels.[59] Brennan concluded that the bleb response seen with all SiHs is significantly less than that seen with conventional hydrogels, but that there was little difference in bleb response between varying SiH materials regardless of their Dk/t. The similarity of response between the SiH materials again highlights this so-called 'law of diminishing returns' with regards to oxygen availability to the cornea with highly oxygen permeable contact lens materials. Clinical results[23,60] would suggest that the SiH material with the lowest Dk/t (galyfilcon A, 86 Barrers, measured polarographically), when compared with the SiH material with the highest Dk/t (lotrafilcon A, 175 Barrers), does not appear to provide the cornea with twice as much oxygen, despite the fact that the Dk/t of lotrafilcon A is almost twice as high. Using an oxygen flux model, the calculated differences are relatively small, with galyfilcon A having an oxygen flux of 97% for open eye conditions, which is only 2% less than lotrafilcon A, which has an oxygen flux of 99% for open eye conditions.[23]

Although the percentage of patients who opt for overnight wear is relatively low, it is very common for patients to doze or nap in their lenses for a period of time. A recent study looked at the impact of dozing or napping for an hour in lenses on corneal thickness increase.[23] The oxygen performance of SiHs was compared with two well-established daily disposable hydrogel lenses. The results showed that there was no significant difference in corneal thickness increase after 'napping' in SiH lenses compared with 'napping' in no lens. However the corneal thickness increases noted with the two daily disposable hydrogel lenses were significantly higher than that seen in both the control (no lens) and the SiHs.[23]

Comfort

The most frequently reported problem with soft CL wear is discomfort and patients will often complain of discomfort and dryness towards the end of the day.[40,61-68] SiH materials have been shown to offer significant benefits in terms of comfort and reduced dryness for many wearers.[40-42, 66, 69-73] The sensation of dryness is related to a variety of factors and it has been suggested that one factor may be dehydration of the lens material,[74,75] although the issue of the role of lens on-eye dehydration on comfort remains contentious.[76] Subjective symptoms of dryness have been shown to occur more frequently in soft lens wearers whose lenses undergo greater levels of dehydration during lens wear.[66,74,75] Research suggests that SiH materials show lower levels of dehydration compared with traditional hydrogel lenses.[77-80]

Schafer et al[71] reported that refitting conventional hydrogel lens wearers with lotrafilcon A resulted in a significant reduction in the percentage of patients who complained of dryness, both during the day and at the end of the day, after just a one week period. The improvement in dryness symptoms remained stable after a three-year follow-up period. The authors concluded that refitting patients with SiH lenses reduced the frequency and severity of dryness symptoms seen with hydrogel lens wear for many patients.

Initial comfort is known to play a big factor in a patients' perception of CLs and is a key part of the success of any CL. Dumbleton et al[40] reported that 93% of existing, successful long-term soft CL wearers were successfully refitted with SiHs for DW. These patients reported no difference in initial comfort from their old lenses. They also found that there was a reduction in end of day dryness and improved end of day comfort compared with their habitual lenses.

Table 3: Made-to-order SiH lenses (ACLM CL Yearbook 2008)

Brand name	AIR OPTIX™ Individual™	Hydrowave SiH®	KeraSoft® 3	Nissel SiH
Material	Sifilcon A	Definitive	Definitive	Filcon II
Manufacturer	CIBA Vision	Ultravision / Contamac	Ultravision / Contamac	Cantor & Nissel
Water content (%)	32	74	74	38
Oxygen permeability ($x10^{-11}$)	82	57	57	115
Replacement frequency	3 month replacement	3 month replacement	3 month replacement	12 month replacement
Prescription range	+20.00 to –20.00 DS	Sph: +30.00 to –30.00 DS; Cyl: -0.50 to –11.00 DC; All axes; Add up to +3.00	To Rx	+30.00 to –30.00 DS
Diameters (mm)	13.2, 14.0, 14.8 (depends on BOZR)	12.5 to 16.5	14.0, 14.5, 15.0	13.0 to 16.0
BOZR (mm)	7.4 to 9.2 (0.3 steps)	7.0 to 9.8	Series A, B, C, D	To Rx

Several other studies have been carried out looking at patient comfort with SiH lenses and also looking at the performance of lenses in challenging environments, such as in front of computers in air-conditioned offices or long periods of driving.[39,41,66,70,81] These studies largely agree that fitting or refitting patients with SiHs can reduce some of the comfort problems experienced by many soft CL wearers, and that these materials may improve comfort in challenging environments.

A recent review of the literature[81] was carried out to ascertain whether symptoms of dryness and discomfort experienced by some wearers of conventional hydrogel lenses might be connected to the level of available oxygen. The review concluded that much of the published literature suggests that patient signs and symptoms seen with hydrogel lens wear may be due to an inflammatory response related to chronic or acute hypoxia and that clinical studies involving highly oxygen permeable SiH materials support a connection between improved comfort and dryness and the level of available oxygen.

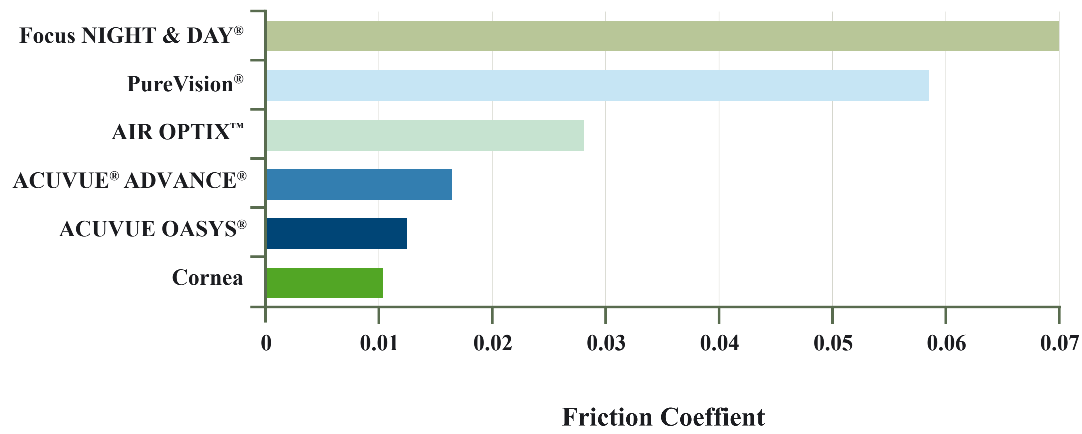
Wettability and lubricity

One significant challenge in the development of SiH materials has been to achieve a highly-wettable lens, since silicone is inherently hydrophobic.[82-91] Different manufacturers have adopted different approaches to convert their materials into wettable lenses,[92] as described below.

Balafilcon A lenses are surface treated in a reactive gas plasma chamber, which transforms the silicone components on the surface of the lenses into hydrophilic silicate compounds.[11,93, 94] Glassy, discontinuous silicate "islands" result,[95,96] and the hydrophilicity of the transformed surface areas "bridges" over the underlying balafilcon A material. These do not completely cover the surface and hence do not affect the permeability of the material. However these islands are sufficiently large and well distributed enough to allow good lens wettability. Lotrafilcon A and lotrafilcon B lenses use a gas plasma technique to apply an extremely thin, uniform, high refractive index, 25nm thick hydrophilic plasma coating on the lens surface after manufacturing,[95-97] which is significantly more wettable than the underlying material. Asmofilcon A uses a combined approach of using plasma polymerization and plasma coating to improve wettability.[98]

More recently introduced lenses do not always need to rely on surface treatment methods to enhance the material wettability. Galyfilcon A and senofilcon A use technology to render the lens wettable without the need for surface treatment.[92,99] The materials contain a moisture-rich wetting agent, high molecular weight polyvinyl pyrrolidone (PVP), which helps to achieve a highly wettable, smooth lens. The wetting agent absorbs moisture and also helps to minimise on-eye dehydration during wear.[100] Comfilcon A[101] and a two-weekly replacement SiH lens for DW (available in the US), Avaira™ with enfilcon A, use technologies to produce a naturally wettable material, again without the need for surface treatment. Air Optix Aqua is plasma-coated lotrafilcon B and employs a hydrophilic moisture agent that is claimed to bind to the lens surface, said to enhance comfort on insertion. It is said to have a lower initial contact angle than the original lotrafilcon B lens.

Figure 3: Coefficients of friction of SiH materials (adapted from reference 106, Ross et al)



Wettability can be assessed both in-vivo and in-vitro.102 In-vitro laboratory measurements, measuring advancing contact angles show that there are differences in the wettability of different SiH materials, and in general SiHs show higher contact angles than conventional hydrogels.[86, 87] Theoretically, materials with the lowest contact angles (and hence better wetting), should prove to be more comfortable in a real world situation. However, clinically there is not as much reported difference in comfort between different SiH products as would have been predicted from contact angle measurements alone. Also, the on eye wettability of SiHs appears to be similar to that reported for conventional hydrogel materials. It is possible that tear film components interact with lens materials after insertion to improve in-vivo wettability,[84,86] which happens in the majority of lenses, to varying degrees. The fact that single contact angle measurements do not adequately predict in-vivo wettability is due to the fact that after a period of wear, any CL material may have slightly different surface characteristics than when initially placed on the eye.

The role of care systems should also be considered when discussing the wettability of CL materials. Modern multi-purpose care systems contain a complex variety of surfactants which clean lenses and also affect the surface wettability.[103-105] In particular some newer solutions, such as OPTIFREE® RepleniSH™, use a combination of wetting agents, humectants and lubricity agents to increase lens wettability with the aim of enhanced comfort.

An additional factor in the comfort of a CL is the interaction that the material has with the upper eyelid. The lubricity of a CL material is a measure of how well the material resists friction. In particular the term relates to the level of friction sustained by the eyelid travelling over the lens surface with each blink, especially if the pre-lens tear film is inadequate.

Lenses with a low coefficient of friction i.e. higher lubricity, may result in less irritation to the upper lid during blinking and give the lens a smooth feel. *Figure 3* shows values obtained for the coefficient of friction for most of the SiH materials available.[106] The addition of an internal wetting agent appears to offer significant advantages in terms of lubricity. In particular, senofilcon A has a very low coefficient of friction, which is similar to the human cornea.[106]

UV protection

Contact lenses with ultraviolet radiation (UVR) blocking properties help to protect ocular tissues from UVR damage, and in particular soft lenses with UV blockers have been found to be effective in protecting against UV obliquely incident light and the peripheral light focussing effect.[107-117] There are a few SiH lenses that incorporate a UV blocking agent in the material.[107,108] The Johnson and Johnson SiH materials are unique in that they all incorporate a Class 1 UV blocker. Galyfilcon A, senofilcon A and narafilcon A meet the strictest standards for UV-blocking, blocking more than 90% UV-A and over 99% UV-B, with galyfilcon A and senofilcon A being the first contact lens materials to receive the World Council of Optometry's global seal of acceptance for their UV protection.[118,119] Enfilcon A (available in the US) also has UV blocking properties.

The second part of this review will look at further material and surface properties of SiHs, including mechanical properties, deposition and solution compatibility, and a variety of complications seen with SiH materials. It will also examine the most recently published evidence on the incidence of inflammatory and infective complications as well as commenting on the future developments for contact lens materials.

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