Soft Contact Lens Material Properties
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Contact lens manufacturers are constantly striving to develop the ‘perfect’ contact lens material, one which satisfies both the patient and practitioner and can be produced cost effectively at a rate which supplies demand. Patient satisfaction, the physiological response of the lens on the eye, reproducibility, predictability and the commercial aspects of the lens are priorities from a practitioner’s perspective. From a patient’s point of view the lens is required to be comfortable, give excellent vision, be easy to handle, convenient and affordable. The aim of this article is to provide an overview of soft contact lens material properties and also highlight the more recent developments in this area.

Hydrogel lenses
The first soft lens monomer hydroxyethyl methacrylate (HEMA), was developed in the late 1950s by Otto Wichterle, however, it wasn’t until the 1970s that the first commercial soft contact lens became available. During soft contact lens production, monomers such as HEMA, with the aid of a catalyst, undergo polymerization to produce a sequence of repeating units termed a polymer. These polymers are bound to each other by the process of cross-linking, creating pores in the material into which fluid can enter. If more than one monomer is used in the material it is termed a copolymer [1]. A polymerised HEMA (pHEMA) lens has a water content of about 38%, however, by varying the monomers used, materials with varying water contents, refractive indices, hardness, strength and oxygen permeabilities can be created.

Silicone hydrogel lenses
Silicone hydrogel (SiH) lenses were launched in 1999 by Bausch and Lomb and Ciba Vision. Silicone elastomers had already been used to create high oxygen permeability lenses but they had poor wettability and comfort, attracted deposits and caused problems with corneal adherence. SiH lenses combined silicone with conventional hydrogel monomers. Silicone is extremely oxygen permeable, even more so than water. The more silicone a lens contains the more permeable it will be. However, silicone is not without its problems; it is hydrophobic and relatively stiff. This created a challenge for the early SiH lens manufacturers as it was necessary to incorporate hydrophilic coatings on the surface of the lenses to give patients the levels of comfort and wettability they desired.

Contact lens material classification
Contact lens materials are classified using the ISO system. BS EN ISO 18369-1: 2006/DAM1 sets out the new international standard method for the classification of contact lens materials [2]. Each material is classified by a 6 part code as shown in Table 1.

Oxygen performance
The passage of oxygen through a contact lens can be quantified in a number of ways. Most commonly quoted by contact lens manufacturers is oxygen transmissibility (Dk/t). The Dk of a material represents its oxygen permeability. In the past this was measured in CGS(FATT) units, however, the International Standard for Dk measurement now recommends using International System Units (SI) instead i.e. changing from the imperial measurements of mmHg to metric measurements of hPa. The units are (cm²/s).[ml.O₂/(ml.hPa)]. Generally Dk is referred to as being in ISO Dk units with values in the order of 10⁻¹¹. The Dk/t of a lens is the Dk of its
material divided by the thickness of the contact lens in cm. FATT units can be converted to ISO units for both Dk and Dk/t by multiplying the value by 0.75.

Generally contact lens manufacturers quote the Dk/t at the centre of a -3D lens. Although this gives practitioners a single number to compare, it tends to overestimate both the Dk/t at the periphery of the lens and also at the centre of lenses of different powers [3]. This is an important factor, as a lower Dk/t, particularly in the periphery of the lens, has been linked to an increase in limbal hyperaemia [4]. It may be more appropriate to use an average thickness when calculating Dk/t and it has been proposed that the mean harmonic thickness may be the best standard to use [5]. Mean harmonic thickness averages the radial thicknesses at the centre of a lens and the periphery of at least five annular zones extending to the edge of the optic zone [6, 7]. It takes into account the thickness of the lens when calculating these zones.

There are two main techniques for measuring the Dk/t of a lens in vitro; polarographic measurement and coulometric measurement. Measurements are dependent on environmental conditions and should be made at 35°C ± 1°C. Errors can occur due to the edge effect and lens dehydration. For this reason, measurements taken by different laboratories must be viewed with caution as they may not be directly comparable. The Dk/t for a number of commercially available lenses are shown in Figure 1.

The normal cornea relies on oxygen from the atmosphere to maintain metabolic activity, and a contact lens on the eye acts as a barrier to this. There is, however, a significant variation in the amount of oxygen an individual cornea requires [8]. The laboratory methods for measuring the passage of oxygen through a lens do not give us any information regarding the amount of oxygen reaching the anterior surface of the cornea per unit time, or how much oxygen is available for the cornea to metabolise. It has been suggested that using oxygen flux (the amount of oxygen which actually passes through a lens on the eye) [9] may be a better way of representing the oxygen performance of a contact lens.

So how much oxygen is enough? A number of studies have produced recommendations as to the amount of oxygen the average cornea requires for daily wear and extended wear of contact lenses [3, 4, 10, 11]. These are listed in Table 2 [10, 11]. The results vary depending on the methodology and the indicator used to determine the critical oxygen value, however, it is generally accepted that a level of 18.1–26.25 ISO Dk units in the open eye and 65.25–66.75 ISO Dk units in the closed eye are necessary.
The oxygen permeability of a conventional hydrogel material increases exponentially with increased water content [12]. As oxygen transmissibility is linked to lens thickness as well as Dk, the thinner the lens the higher the Dk/t, therefore for optimum Dk/t a hydrogel lens would be very thin with a high water content. In practice, however, this creates a fragile lens that dehydrates quickly and would therefore not be acceptable from a patient’s point of view. As a compromise, lenses have tended to be manufactured from mid water content materials (55-60%) with centre thicknesses of around 0.08 mm. This, however, does not provide a high enough Dk/t to meet the critical oxygen requirements of the cornea. The recent development of a high water content, bio inspired material (Hypergel) with a Dk/t of 42 ISO units, aims to tackle both the oxygen transmissibility and dehydration issues.

SiH lenses also contain water, however, the Dk of the material is dependent on the silicone content of the material, as silicone transports oxygen better than water. If water is removed from the material and replaced with silicon the Dk increases [12]. The introduction of SiH materials has reduced concern about corneal hypoxia, particularly in daily wear lenses, as these lenses all meet the critical oxygen requirements of the cornea both centrally and peripherally. It appears, however, that high Dk/t alone does not guarantee lens comfort or corneal integrity, as these factors are influenced by a number of other material properties such as modulus, wettability, biocompatibility, friction and deposit resistance.

**Modulus**

The modulus of a material describes its ability to keep its shape and resist deformation. The modulus of a contact lens is measured using Young’s modulus (E), measured in megapascals (MPa) and is described as the ability of a lens material to align to the ocular surface and resist deformation under tension. It is the ratio of stress to strain: stress being the force per unit area required to change the shape of a solid, and strain being the deformation undergone by the sample in the direction of the force applied during testing [13]. Modulus is an inherent property of the material itself, and the stiffness of a contact lens is also dependant on its design and thickness. The modulus values for some of the currently available SiH contact lens materials are shown for comparison in Figure 2, however, at present there is no standardised method of measurement, which means comparison of figures from different sources must be made with caution.

![Figure 2](image-url)
The early SiH lens materials (lotrafilcon A; Night and Day and balafilcon A; PureVision), have a modulus two or three times higher than that of pHEMA. This higher modulus makes the lenses easier to handle (an advantage for older, presbyopic patients), however, evidence suggests a relationship between some of these high oxygen transmissibility, high modulus materials [14] and some non-inflammatory ocular complications such as superior epithelial arcuate lesions (SEALs) (Figure 3), mucin balls and contact lens induced papillary conjunctivitis (CLPC) (Figure 4). As stiffer lenses tend not to drape the cornea in the same way as a conventional hydrogel, fluting has been seen around the edges of these high modulus lenses suggesting more practitioner skill and additional parameters may be needed to achieve a successful fit. Anecdotal evidence suggests that patients are initially more aware of SiH lenses than conventional hydrogels and a correlation between increased modulus and decreased comfort has been indicated [15], however, it appears that the majority of hydrogel lens wearers can be refitted with a SiH material with no comfort issues [16]. Surprisingly, there is evidence that the increased Dk/t of SiH lens materials has not reduced the incidence of microbial keratitis and inflammatory events as compared to conventional hydrogel lenses, even on a daily wear basis [17]. This suggests the benefits of high Dk SiH materials may be offset by the relatively high modulus [18] with corneal insult possibly being a precursor to microbial infection.

Figure 3 SEAL

Figure 4 contact lens induced papillary conjunctivitis (CLPC)
Later SiH lens materials such as galyfilcon A (Acuvue Advance) and comfilcon A (Biofinity) have a lower modulus which may make them more acceptable to the patient, with greater initial comfort and less lens awareness. In theory there is also the possibility of less ocular insult and therefore a lower rate of inflammatory events and microbial infection, however, at present there is little scientific evidence to support this.

Contact lens surface characteristics

The surface characteristics of a contact lens, such as wettability, biocompatibility and lubricity, and the interaction they have with the ocular surface and eyelids are extremely important when considering patient comfort. Placing a lens on the cornea interferes with the normal tear film as it separates it into two layers; the pre-lens and post-lens tear films. Ideally the contact lens needs to mimic the wettability of the cornea enabling the formation of a good, stable pre and post-lens tear film which in turn will give clear vision and good comfort throughout the day.

Wettability is the ability of a liquid to adhere to a solid surface, and is determined by a balance between the adhesive and cohesive forces acting on the surface [19]. Cohesion is the attraction between molecules that are the same i.e. the force which holds a drop of liquid together. Adhesion is the attraction between dissimilar substances i.e. the contact lens surface and the tears. A drop of liquid is created because the surface molecules are pulled inwards by the adhesive forces within the liquid. These forces are unopposed which means the outer molecules have excess potential energy; known as surface tension. The lower the surface tension of a liquid the more likely it is to spread across a solid surface. The surface tension of tears can be reduced by using wetting drops during lens wear. When a drop of liquid comes in to contact with a solid surface the excess potential energy that the molecules at the surface of the liquid have is reduced by attraction to molecules at the surface of the solid. This new energy value is the interfacial tension, and the lower this is the greater the attraction between the liquid and solid will be, therefore improving wettability. Using wetting solution on lens insertion will reduce the interfacial tension between the tears and lens. Finally increasing the surface tension of a solid improves wettability and this can be achieved by surface treatment of the contact lens.

The wettability of a material can be measured in vitro using the contact angle which is formed when a drop of liquid is placed on a solid surface (Figure 5). Its size can be used to provide an indication of how wettable a surface is. There are various methods of measuring contact angle; the three most common being the Sessile drop, Captive bubble and Wilhelmy balance techniques. The smaller the contact angle the more wettable the surface, however, the method used affects the resulting measurement [20]. Manufacturers’ quoted measurements of wettability must therefore be compared with caution, although independent research has shown them to be reasonably accurate at room temperature [12].
These *in vitro* measures do not necessarily relate to the *in vivo* performance of a contact lens. *In vivo* wettability is much more difficult to measure. It is often done in practice using slit lamp biomicroscopy or keratometer mires, however, these are relatively subjective techniques. Researchers are constantly striving for more quantitative methods of measuring in *vivo* contact lens wettability and a method of measuring the contact angle on the eye has recently been developed [21]. The difficulty in acquiring consistent, quantitative, on eye measurements may be the reason studies have found that symptoms of dryness do not necessarily appear to correlate with signs [22, 23].

Two properties of the material itself can affect the wettability of hydrogel lenses [19]. The first is that they dehydrate throughout the day therefore becoming less wettable, and the second is that the polymer chains making up the materials have both hydrophilic and hydrophobic groups. These polymer chains are mobile and the hydrophilic groups can rotate towards the lens surface if exposed to water, but away from the lens surface if they come in to contact with a hydrophobic surface such as air or lipid from the tear film.

Lubricity is a relatively new concept in the world of contact lenses. It is also referred to as the coefficient of friction (CoF) of a lens and is quantitatively measured by microtribometry. It refers to how smooth and slippery the surface of a lens is, which in turn affects the friction between the lens and eyelid. A low CoF allows the eyelid to flow over the surface of the lens and improves patient comfort [24]. Figure 6 shows the CoF for a number of contact lenses on the market [25]. At present there is no standard method of measurement for CoF making comparison between measurements from different sources difficult.

![Figure 6](image)

Various techniques have been used by the contact lens industry to improve the wettability, biocompatibility and lubricity of conventional hydrogel lenses. Biocompatibility describes the ability of the lens to be in harmony with the eye and have little or no adverse effects on the ocular surface. Biomimisis is the development of artificial biomaterials that mimic natural forms and effects, and is the concept behind the material omafilcon A (Proclear). This material contains a synthetic analogue of a naturally occurring phospholipid (phosphorycholine) which encourages moisture retention. Etafilcon A (1 Day Acuvue Moist), contains a hydrophilic polymer which is embedded in the matrix of the material. In nelifilcon A (Dailies AquaComfort Plus), blink action is used to release a moisturising agent, Polyvinyl Alcohol (PVA) throughout the day. The majority of the PVA is bound within the matrix of the lens, however, a small amount is free and is released.
throughout the day. Ciba Vision have gone a step further and added hydroxypropylmethyl cellulose (HPMC) to the saline storage solution for comfort on insertion, and the hydrophilic wetting agent Polyethylene Glycol (PEG) into the lens to provide comfort early on in the day and to bind to the PVA to slow its release. There is evidence this technology produces a more stable pre-lens tear film [26].

New materials are constantly being developed to address the issue of biocompatibility and wettability. A new daily lens has been developed from a bio inspired material (Hypergel) which has the same water content as the cornea (78%). The outer surface is designed to mimic the lipid layer of the tear film to prevent dehydration and maintain constant optics. The lens does not contain silicone, however, it has a Dk/t of 42 ISO units at the centre of a -3.00D lens, which is adequate for oxygen delivery to the cornea in open eye conditions by delivering an oxygen flux percentage of 93%.

Silicone is a naturally hydrophobic material and the challenge faced by the lens manufacturers was to develop methods of making SiH lenses more wettable and therefore more acceptable to the ocular surface. One method of achieving this is surface treatment, which was the technique used by the manufacturers of the early SiH lenses [27]. Two different technologies were used in an effort to create a hydrophilic surface. The first was a permanent, ultrathin (25 nm), uniform, high refractive index plasma coating on the surface of the lenses (lotrafilcon A; Night and Day). The second method was a plasma oxidation surface treatment resulting in glassy silicate islands (balafilcon A; PureVision). The gap between the islands is so small that their wettability bridges the hydrophobic balafilcon. The flow of oxygen and fluids is not impeded by these surface treatments, however, studies have shown that these methods have only been partially effective, resulting in reduced wettability and increased deposition [28]. With the introduction of later SiH materials, the issue of wettability has been approached differently by using internal wetting agents such as polyvinylpyrolidone (PVP) (senofilcon A; Acuvue Oasys and galyfilcon A; Acuvue Advance), silicone macromers to produce a naturally wettable lens (comifilcon A; Biofinity) and a packaging solution containing a moisturising surfactant (polaxamine) designed to improve comfort on insertion (balafilcon A; PureVision).

A daily disposable lens which has recently been released into the market in Europe (Dailies Total1) aims to solve the problem of SiH wettability. It is a water gradient SiH material with the water content increasing from 33% at the core of the lens to over 80% at the surface.

Figure 7
Lenses dehydrating outdoors in a dehydration test at a recent CET meeting
Are SiH lens materials less prone to dehydration than conventional hydrogels? SiH materials are by their nature less wettable than conventional hydrogel lenses, however, lens manufacturers are striving to remedy this. SiH materials have a lower water content than conventional hydrogel lenses, which may possibly make them less prone to dehydration. At present the answer is equivocal and further investigation is necessary. There are a number of studies which suggest the biocompatible material omafilcon A (Proclear) dehydrates less than some SiH lenses, however, studies which involved refitting conventional hydrogel patients with SiH lenses have suggested they report reduced dryness [16] and longer wearing times [29].

**Lens Deposition**
Deposition of tear film components on a contact lens surface causes a reduction in the overall performance of the lens and an increase in inflammatory responses (Figure 8). There are various factors which influence deposition on contact lens materials such as tear film composition, the ionicity of the material, water content, pore size and hydrophobicity. A large proportion of the protein in the tear film is lysozyme, and group IV materials (ionic, high water content) tend to attract this protein to a greater extent than the other groups. Group II (non-ionic, high water content) lens materials have a tendency to attract lipids from the tear film. Some SiH materials have been found to deposit considerably less protein and more lipid than conventional hydrogels, however, the pattern of deposition appears to depend on the formula of the material and whether it is surface treated [28, 30]. There is also the possibility that a higher percentage of denatured proteins accumulate on some SiH lenses as the protein is not able to penetrate the matrix of the lens due to surface treatment. This may contribute to the increase in CLPC which has been reported with some SiH materials [14].

![Figure 8 Deposits on a soft contact lens](image)

**Antimicrobial lens surfaces and materials**
SiH lens materials have reduced practitioners’ concerns regarding the supply of oxygen to the cornea, however, studies have shown the risk of infection to be similar for SiH lenses as it is for conventional hydrogels [17]. This risk is highest when lenses are worn on an extended wear basis and lowest for daily disposables. If this risk is to be reduced, further developments in contact lens materials are necessary. During contact lens wear bacteria adhere to biofilms which build up on the lens surface. Surface techniques are being developed with the aim of preventing biofilm formation and acting to kill the bacteria. Silver is an
antimicrobial agent with a low toxicity to human tissue and is already used to reduce microbial contamination in contact lens cases (AQuify, Ciba Vision). A glass powder is added to the case material during manufacture, and on contact with the moisture from the solution, silver ions with their antimicrobial properties are released. Clinical studies have shown there to be a significant reduction in lens contamination using this technology [31]. There are also a number of other technologies being investigated for their use with medical devices which could possibly be applied to contact lens materials [32]. These include polyquats, polymeric pyridinium compounds, free radical-producing agents, quorum-sensing blockers and antiinfective agents. This type of technology could revive interest in overnight wear of lenses as extended wear has the highest risk factor for corneal infection regardless of lens material. It would also be of benefit if applied to daily wear materials as contact lens patients are not always compliant with their care regimes and extra protection against microbial infection would be provided. An antimicrobial lens would need to be compatible with the ocular surface, not elicit an allergic response, be wettable and not attract deposits and be compatible with the lens care regime. Ease of manufacture and cost effective production must also be taken into consideration.

Conclusion
The development of silicone hydrogel contact lens materials, which reduced concerns regarding oxygen supply to the cornea during daily contact lens wear, was a huge step forward for the contact lens industry. A silicone containing material, however, does not necessarily produce a ‘perfect’ lens or provide the best wearing experience for the patient. Properties such as visual quality, lubricity, modulus, wettability, de-hydration and antimicrobial surface treatment have now become the focus of research. Contact lens manufacturers are rising to the challenge and over the next few years practitioners will no doubt see a number of advances in material technologies to meet the needs of the wearer.