

The decay of Dk?

In the first of three articles looking at contact lens material properties, **Dr Philip Morgan and Dr Noel Brennan** review the measurement of the oxygen performance of soft contact lenses and the clinical relevance of these measures for currently available contact lenses. CET Module C4836c

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A SUCCESSFUL CONTACT LENS needs to provide acceptable levels of vision, comfort, handleability/usability and physiological response. The first three parameters are of primary concern to the wearer and are usually immediately apparent. The final requirement – an acceptable physiological response – is usually of greater concern to the contact lens practitioner and is usually of medium and long-term concern.

Very broadly, the various forms of adverse physiological ocular response to contact lenses can be attributed to mechanical or lens surface effects, and hypoxia-related phenomena.¹ Mechanical effects include papillary conjunctivitis, superior epithelial arcuate lesions and conjunctival staining. Hypoxia-related adverse responses include limbal redness, some types of corneal staining and, most seriously, microbial keratitis.

One of the measures, therefore, of the physiological performance of a contact lens, relates to the amount of oxygen which reaches the ocular surface from the atmosphere. This is most important in the central and anterior parts of the cornea. The corneal periphery may derive some of its oxygen supply from the local vasculature, whereas the posterior layers are supplied by the aqueous humour. However, the central anterior cornea is very dependent on atmospheric supply.

Given this, it is desirable to have some measure to indicate the oxygen performance of a contact lens. For more than 30 years, the best-known measures in this area have been the oxygen permeability of the materials from which lenses are fabricated, and oxygen transmissibility – the oxygen performance of a finished, manufactured lens.

PERMEABILITY AND TRANSMISSIBILITY

In the materials science literature, the gas permeability of a membrane is given as the product of the diffusivity (D) of the material to the gas (the ease with which the gas can move through the material) and the solubility (S) of the gas within the membrane material (the amount of gas which is present in the material).² That is:

$$\text{Permeability} = DS$$

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In the contact lens literature, it has become the norm to represent solubility as 'k', so:

$$\text{Permeability} = Dk$$

It is important to consider that permeability is a property of a material. The oxygen performance of a manufactured contact lens is partly a function of the permeability of the material from which the lens is made, but is also related to the thickness of the lens.

For example, if two lenses are made from the same material but one has twice the thickness of the other, then the oxygen performance of the thicker lens will be half that of the thinner lens.

When thickness is taken into account, the term oxygen transmissibility is used:

$$\text{Transmissibility} = Dk/t$$

The 'thickness' of a finished contact lens is potentially a contentious issue, and any reporting of lens transmissibility should include details of the thickness which is used. This can be the thickness of the geometric centre, or of any other part of the lens.³ Commonly, however, the thickness

of the central zone (usually of 6mm in diameter) is used. The rationale behind this value is both pragmatic and clinical.

From the pragmatic standpoint, the central 6mm falls within the optical zone of the lens which means that if the central thickness is measured, and other lens parameters are known (such as lens power and water content), the average thickness of the central zone can be mathematically calculated.

Clinically, the central lens area is more likely to be of interest because this is the part of the cornea which is wholly reliant on the atmosphere for its oxygen supply.

WHAT GOVERNS PERMEABILITY?

For conventional hydrogel materials (soft hydrogel lens materials, except silicone hydrogels), the factor which determines permeability is surprisingly simple: water content.

The term 'hydrogel', of course, refers to a gel-like material which contains water. Oxygen reaching the ocular surface must pass through the water within the material. That is, the lens polymer itself is impermeable to oxygen. The first hydrogel lenses were manufactured from poly (hydroxyethylmethacrylate) (pHEMA) which has a permeability of about seven units (see panel on Units of Dk and Dk/t over the page).

As the importance of oxygen permeability became better understood, manufacturers sought to increase the water content of their materials by adding other monomers to the lens material. A common approach in contact lens manufacture is to add methacrylic acid to increase the water content of the polymer from the 38 per cent of pHEMA to 50-60 per cent.

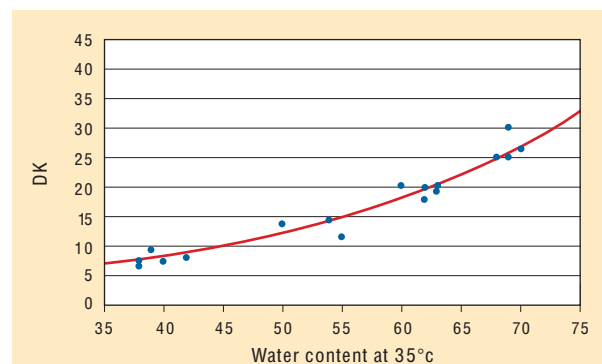
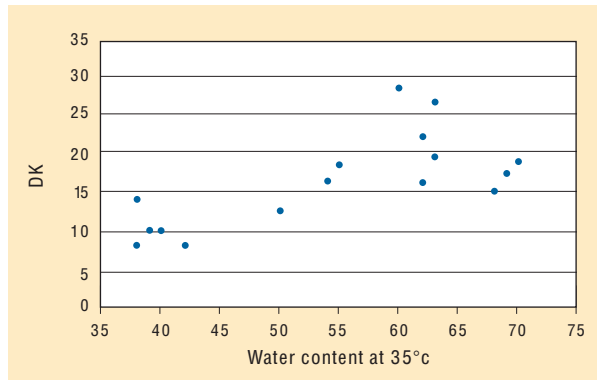


FIGURE 1. Relationship between water content and oxygen permeability. Water content is per cent. See section on 'Units for Dk'. Based on Morgan and Efron (1997)

FIGURE 2. Oxygen transmissibility for a range of commercially available lenses in -3.00DS power. There is a general increase in transmissibility with water content, but at this power, the reduced thickness of the mid water contact lenses outweighs the greater permeability afforded by the high water content materials. Water content is per cent. See panel below on 'Units' for Dk/t units. Based on Morgan and Efron (1997)



Another method is to use vinyl pyrrolidone or other hydrophilic monomers to provide materials with water content values of over 70 per cent.

Increasing water content causes an increase in 'D' and 'k' such that water content is exponentially related to the permeability of the lens material. Figure 1 depicts the relationship between permeability and water content (W) for conventional hydrogels found by Morgan and Efron.⁴ They demonstrated:

$$Dk = 1.67e^{0.0397W}$$

DOES GOOD PERMEABILITY MEAN GOOD TRANSMISSIBILITY?

While the permeability of a contact lens material is of interest to clinicians, a much more relevant measure is that of transmissibility, when thickness of the lens is taken into account and the oxygen performance of the contact lens itself is presented.

If lens thickness were similar for all material water contents for a given lens power, then the lenses made from materials with the greatest permeability would offer the best transmissibility. However, this is not the case.

Materials of a very high-water content (over 70 per cent) cannot be made very thin because:

- ◆ This is difficult from a manufacturing standpoint
- ◆ Thin, high-water content lenses cause central corneal staining through a mechanism which is not well understood, although it has been suggested that this might be related to local dehydration of the corneal epithelium.⁵

In fact, analysis of a range of commercially available lenses shows that the thinnest available lenses are those of low-water content (about 38 per cent) and mid-water content (55-60 per cent).⁴

When transmissibility is assessed for lenses which are -3.00DS in power, the reduced thickness of the mid-water content lenses outweighs the high permeability of the high-water content lenses, and it is the mid-water lenses which offer the best oxygen transmissibility (Figure 2).

WHAT FACTORS CAN AFFECT OXYGEN TRANSMISSIBILITY?

The oxygen transmissibility of a conventional soft hydrogel is influenced by a number of factors. For example, as transmissibility is represented as 'Dk/t', factors which alter either permeability (Dk) or lens thickness (t) will alter transmissibility.

The relationship between water content and permeability was detailed earlier and suggests that any change in water content will alter lens permeability. Such factors could include temperature, pH and on-eye dehydration. While the first two factors are unlikely to have any major effect, dehydration is known to vary between materials.

Efron and Morgan (1999)⁶ demonstrated that lenses could lose up to 6 per cent of absolute water content and

that this will reduce lens transmissibility. Furthermore, it appears that on-eye dehydration is material dependent, and that lenses classified as 'ionic' (principally those containing methacrylic acid) tend to dehydrate on-eye more than non-ionic lenses.

Changes in lens thickness have a significant impact on lens transmissibility and, of

course, changes in back vertex power are dependent on changes in lens thickness.

Figure 3 shows the change in transmissibility across minus and plus powers for three lens brands representing low-water, mid-water and high-water content lenses.

In low minus powers, mid-water content lenses provide the best transmissibility, although the higher water content lens performs better in the higher minus powers.

It is of note that there is no significant tear exchange with soft contact lenses (about 1 per cent of tear volume is replaced with each blink⁷ compared with about 15 per cent per blink with lenses⁸) and there is no lateral movement of oxygen behind a contact lens,⁹ reinforcing the role of lens transmissibility in the oxygenation of the corneal surface.

Units for Dk and Dk/t

Formally, permeability in the contact lens field is measured in the unit 'Barrer' which is represented as:

$$10^{-11} \text{ cm}^2 \text{ mlO}_2 \text{ s}^{-1} \text{ ml}^{-1} \text{ mmHg}^{-1}$$

Often, these units are referred to as 'Fatt units' after the pioneer of contact lens permeability measurement, Dr Irving Fatt.

Transmissibility requires the division of permeability by thickness, with the units:

$$10^{-9} \text{ cm mlO}_2 \text{ s}^{-1} \text{ ml}^{-1} \text{ mmHg}^{-1}$$

The modification of the 10⁻⁹ term within these units means that a contact lens with a thickness of 100µm (0.1mm) will have the same numeric value for permeability and transmissibility. As this thickness (about 100µm) is a typical value for a contact lens, it is common to see permeability values which are very similar to lens transmissibility values.

Some reports feature transmissibility values in Barrer/cm but then proceed to present numerically similar permeability and transmissibility values. However, this would only be the case if lens thickness was 1cm – some 100 times greater than a normal value.

A lens with permeability of 20 Barrer and

a thickness of 100µm has a transmissibility of 0.2 Barrer/cm or possibly 20 x 10⁻² Barrer/cm, but not 20 Barrer/cm.

Further potential confusion arises because of the requirement of the International Standard to use metric units. As 'mmHg' is classified as an imperial measure, the metric equivalent is hectopascal (hPa). Thus, the ISO units for permeability are:

$$10^{-11} \text{ cm}^2 \text{ mlO}_2 \text{ s}^{-1} \text{ ml}^{-1} \text{ hPa}^{-1}$$

and for transmissibility are:

$$10^{-9} \text{ cm mlO}_2 \text{ s}^{-1} \text{ ml}^{-1} \text{ hPa}^{-1}$$

Conversion from traditional to ISO units requires multiplication by 0.75, and therefore a reduction in headline values.

The oxygen performance of the same lens could be expressed as either 20 traditional units or 15 ISO units. Perhaps because of the negative impact of this apparent reduction, the use of ISO units remains very unusual in the research literature. As such, traditional units are used throughout this paper. Where transmissibility is reported in this paper, thickness is taken as an average across the central 6mm.

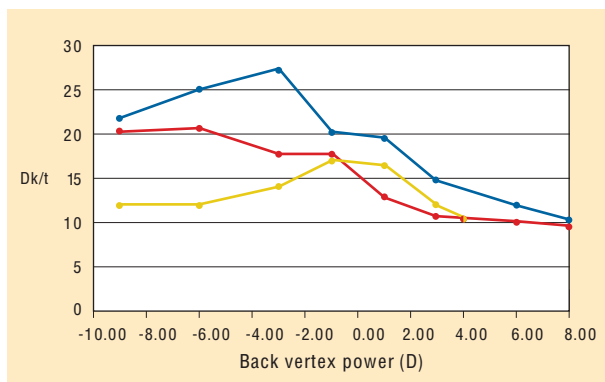


FIGURE 3. Change in oxygen transmissibility over a range of back vertex powers for representative low water content (LWC), mid water content (MWC) and high water content (HWC) lenses. See section on 'Units for Dk/t' opposite. Based on Morgan and Efron (1997)

MEASUREMENT OF PERMEABILITY AND TRANSMISSIBILITY

Two techniques for the measurement of contact lens oxygen performance have international standards outlining their implementation in laboratories.

The first requires the use of a polarographic electrode¹⁰ and the second a coulometric set-up,¹¹ although most published values have been measured using the former method due to its relatively low cost and general acceptance.

The polarographic system requires the placement of a contact lens onto the surface of a polarographic electrode in a humidified environment at ocular temperature (nominally 35°C). This electrode measures the electrical current which flows as a result of the cathodic reduction

of the oxygen which reaches its surface (Figure 4). That is, the greater the amount of oxygen that is able to pass through the contact lens, the greater the electrical current within the electrode; this current is readily measured with an ammeter and can be related back to the transmissibility of the sample.

There are two important errors which can be introduced into the measurement of oxygen permeability using this system.

The first is due to the barrier presented by the layer of fluid which is trapped between the lens and the electrode.¹² This acts to reduce the amount of oxygen reaching the electrode surface and is termed the 'boundary effect'. This can be accounted for by measuring the transmissibility (Dk/t) of a number of material samples – each of different thickness (t) –



FIGURE 4. Draping a soft lens over a polarographic electrode for the measurement of oxygen performance

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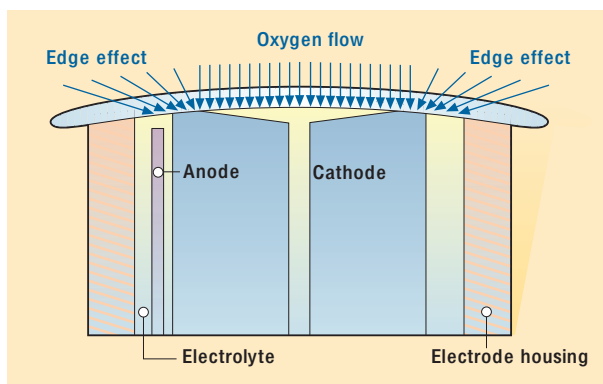


FIGURE 5. Schematic representation of the edge effect. Taken from Brennan, Efron and Newman (1987)¹³

and obtaining Dk by assessing the gradient of a graph plotted of the Dk/t measures against the values for t .

While the first error is essentially a typical resistance error for this form of gas permeability assessment, the second is more peculiar to contact lenses and is more contentious – the ‘edge effect’.

One assumption which is made for this form of gas measurement is that the thickness of the membrane (the lens) is infinitely thin with respect to the diameter of the underlying electrode. This assumption is important because it can then be assumed that all oxygen which reaches the electrode has passed perpendicularly through the lens.

However, it is apparent that this assumption is violated in the case of contact lens assessment, and that oxygen

is able to move laterally through the contact lens in order to reach the surface of the electrode¹³ (Figure 4). This ‘edge effect’ allows more oxygen through to the surface of an infinitely thin membrane and needs to be accounted for.

The International Standard presents a simple mathematical correction process which is related to the diameter of the cathode and the thickness of the contact lens. In practice, it accounts for a 20-25 per cent reduction in the values recorded by the system.

The correct values for oxygen permeability and transmissibility must take account of the boundary and edge effects. However, it is clear that manufacturers tend to cite either ‘uncorrected’ or ‘corrected’ values, or both. The main issue

is that correction for the edge effect reduces permeability scores which may put materials with correctly cited values at a commercial disadvantage to those which are incorrectly cited.

SILICONE HYDROGELS VERSUS CONVENTIONAL HYDROGELS

While the polymers used in conventional contact lens hydrogels are inherently impermeable to oxygen (and any permeability is via the water contained within the material), there are many polymers with an inherent ability to transmit oxygen. In particular, polymers containing siloxane groups are known to offer high levels of oxygen permeability.

In 1999, Bausch & Lomb and Ciba Vision launched the PureVision and Focus Night & Day silicone hydrogel lenses, respectively. These lenses both sought to combine the comfort and wettability of conventional hydrogels with the oxygen performance of siloxane-containing materials.

The UK launch of Johnson & Johnson’s silicone hydrogel lens, Acuvue Advance, is expected any month now after it was made available in the US late last year. Whereas the PureVision and Focus Night & Day lenses are primarily marketed for extended wear, Acuvue Advance is a daily wear product.

A consequence of these combined

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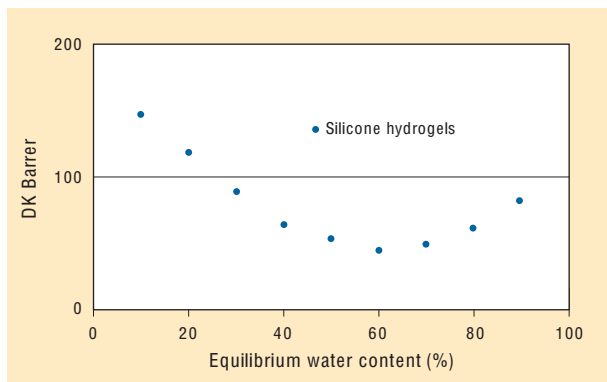


FIGURE 6. Variation in oxygen permeability with water content for a family of silicone hydrogel materials. Based on Tighe (2000)¹⁹

materials is that oxygen permeability increases with decreasing water content. This is because water is less permeable to oxygen than siloxane-containing groups, so permeability will increase as the relative amount of siloxane-containing groups increases and water content decreases.

Tighe (2000)¹⁴ has presented the relationship between water content and oxygen permeability and for a family of silicone hydrogels (Figure 6).

CAN Dk SURVIVE AS A MEASURE IN THE SILICONE HYDROGEL ERA?

In this discussion about oxygen performance, it is important to keep the various measures in perspective. Clinicians are interested in the performance of a contact lens with respect to its impact on the physiology of the ocular surface. As such, they need to consider the amount of oxygen which reaches the ocular surface – ‘oxygen flux’. Oxygen flux indicates the

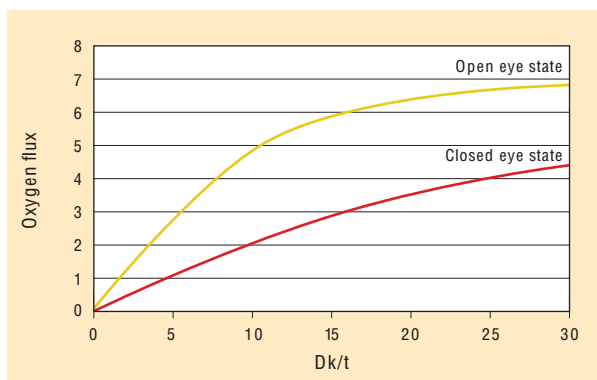


FIGURE 7. Oxygen flux for conventional hydrogel lenses

volume of oxygen which reaches a unit area of the corneal surface in unit time.

In a number of ways, therefore, this is a more important clinical parameter than lens transmissibility, a laboratory measure which takes no account of ocular conditions.

That said, for the range of oxygen permeability values offered by conventional hydrogels, there is something approaching a linear relationship between transmissibility and flux.

Figure 7 presents oxygen flux for low values of transmissibility using a mathematical model proposed by Brennan.¹⁵ It is evident that increases in

transmissibility afford similar proportional changes in flux. As such, for conventional hydrogels, presenting values for oxygen transmissibility for contact lenses is reasonably informative in terms of understanding the amount of oxygen which reaches the ocular surface.

However, if this graph is expanded upon to incorporate higher levels of oxygen performance (Figure 8), it is clear that we are studying a system of ‘diminishing returns’. That is, as measured contact lens oxygen permeability rises, the increases in delivered oxygen to the cornea reduce in magnitude. This relationship is evident when considering Fick’s first law:

$$\text{Oxygen flux} = Dk/t \Delta P$$

where ΔP represents the difference in oxygen tension between the front and the back of the lens.

The tension at the front of the lens is assumed to be constant (159mmHg and 59mmHg for the open eye and closed eye states, respectively¹⁶), but the tension at the back of the lens is itself dependent on the transmissibility of the contact lens. It is helpful to consider ΔP as a

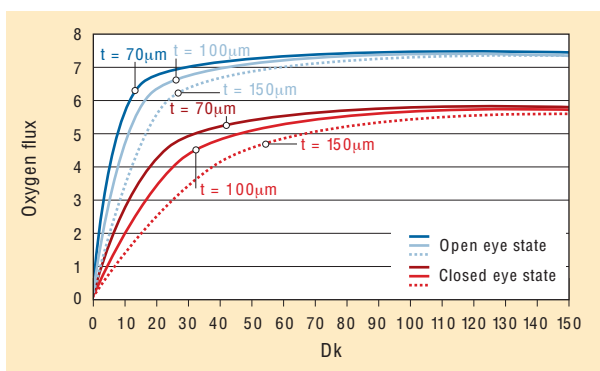


FIGURE 8. Oxygen flux versus oxygen permeability for a range of average lens thicknesses and for open eye and closed eye states

TABLE 1. Oxygen transmissibility and flux for a range of representative contact lenses

Lens	Dk/t ¹	Open eye flux ²	% of maximum	Closed eye flux ²	% of maximum
100µm thick HEMA lens	7.5	3.95	52%	1.50	25%
Acuvue 2	26	6.65	88%	4.09	68%
Acuvue Advance	86	7.31	97%	5.55	92%
PureVision	110	7.37	98%	5.68	94%
Focus Night & Day	175	7.44	99%	5.84	97%
No lens	Infinite	7.54	100%	6.04	100%

¹ Manufacturers’ values for -3.00DS lenses. ² Units are µl cm⁻² h⁻¹

TABLE 2. Published thresholds for satisfactory closed-eye contact lens wear based on a range of rationales

Author	Rationale	Dk/t	Flux*	% of no lens situation
Papas (1998) ²⁰	Absence of induced limbal hyperaemia (lower 95% confidence interval)	56	5.25	87%
Holden & Mertz (1984) ¹⁸	Corneal swelling with lens wear of 4%	87	5.57	92%
Harvitt & Bonanno (1999) ²¹	Absence of epithelial anoxia	89	5.58	92%
Sweeney (2000) ²²	Corneal swelling with lens wear of 3.2%	125	5.73	95%
Papas (1998) ²⁰	Absence of induced limbal hyperaemia (mean result)	125	5.73	95%
Papas (1998) ²⁰	Absence of induced limbal hyperaemia (upper 95% confidence interval)	274	5.93	98%
Giasson & Bonanno (1994) ²³	Absence of epithelial pH change	300	5.94	98%

*Units are $\mu\text{l cm}^{-2} \text{h}^{-1}$

'pressure gradient'.

There is a greater tendency for oxygen to pass to the ocular surface when this pressure gradient is high. Clearly, therefore, the maximum possible oxygen tension at the back of the lens is equal to that at the front of the lens.

On this basis, it seems straightforward to construct an argument that the use of Dk and Dk/t values in the era of silicone hydrogels is not appropriate. Oxygen flux is a strong contender for replacing these parameters, although Brennan, in particular, has argued for a more sophisticated and physiology-based approach which considers the amount of oxygen actually consumed by the cornea.¹⁷

Figure 8 demonstrates that below 30 units (that is, for the conventional hydrogels), changes in oxygen permeability are accompanied by relative large changes in oxygen flux. However, beyond this value, any increases in oxygen flux are much smaller. Theoretical materials offering permeabilities of 500 or 1,000 units will not deliver significantly more oxygen to the cornea than current materials. Table 1 indicates the oxygen flux with a range of contact lens types for open and closed eye conditions.

HOW MUCH OXYGEN DOES THE CORNEA REQUIRE?

A vital question in understanding the issues relating to contact lens oxygen performance is the amount of oxygen which is required for normal corneal physiology.

This has been addressed in many different ways historically. For open-eye (daily wear) conditions, the best-known value is that of Holden and Mertz (1984) who suggested that a lens with Dk/t of 24.1 units would not induce corneal swelling during daily wear.¹⁸ At the time of the work, permeability values were not normally edge-corrected, and the edge-corrected equivalent value is 21.8 units.

The situation for overnight wear is more complex (Table 2). Holden and Mertz (1984) found that a lens with a

transmissibility of 87 units (73 units if edge-corrected values are employed) would limit overnight corneal swelling to 4 per cent – a value considered to be that of a non-lens wearer.¹⁸ Subsequent workers, using a variety of rationales have reported thresholds from 56 to 300 units.

Superficially, this seems a huge range of values which must be in contradiction with each other. When these values are considered as flux measures, this five-fold increase from the lowest to the highest presented threshold is reduced to a 13 per cent difference between the two extremes.

In other words, these researchers are in fact finding data which is in general agreement, but the presentation of such thresholds in terms of oxygen transmissibility is potentially confusing.

One issue which is generally ignored is that of variation of corneal physiology within a human population. It seems reasonable to present threshold values at which a contact lens will provide sufficient oxygen for normal corneal physiology. However, as there is a range of corneal responses, presenting the threshold for an average cornea may not be appropriate: clinicians should be able to offer products which will meet the physiological requirements of the great majority of their patients. This issue needs to be addressed in future research in this area.

SUMMARY

A number of key points are apparent in the understanding of the oxygen performance of soft contact lenses.

Oxygen permeability for conventional hydrogels, rather than being a mysterious value of unknown origin, is directly related to water content. If the average central thickness of a contact lens for a particular power (usually -3.00DS) is known, both permeability and transmissibility can be readily calculated mathematically.

It is sensible that manufacturers have settled on citing transmissibility values for -3.00DS lenses, but factors such as thickness differences, due to varying lens

power, and dehydration, can impact on oxygen performance.

Most cited oxygen performance values have been generated using a polarographic method which has some accompanying errors. These are easily corrected using methods in an international standard, and manufacturers should cite fully corrected values for their data.

Silicone hydrogel lenses offer a significant increase in oxygen transmissibility; however, increases in laboratory lens measures (Dk and Dk/t) are not linearly related to clinical values (oxygen flux) and the relationship between these values is one of diminishing returns.

In fact, this relationship suggests that our clinical understanding of the physiological impact of contact lenses in the era of silicone hydrogel lenses is hampered rather than aided by the exclusive use of Dk and Dk/t. Oxygen flux or other more physiologically relevant measures should now be considered.

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MULTIPLE CHOICE QUESTIONS

1 Which contact lens-related adverse event is considered to be related to reduced oxygen supply to the ocular surface?

- A Limbal hyperaemia
- B Superior epithelial arcuate lesion
- C Papillary conjunctivitis
- D Conjunctival staining

2 Why is permeability termed 'Dk'?

- A It is the product of two parameters 'D' and 'k'
- B It is based on the Latin *Dorus karmisarum* which approximately translates as 'air through silk'
- C It relates to two fixed constants 'diffusability' and 'solubility'
- D Permeability is defined as Dk/t

3 In Dk/t, what does the 't' normally represent?

- A Average thickness over the central area of a contact lens
- B Thickness at the contact lens centre
- C Mean thickness across the contact lens
- D Maximum lens thickness

4 Which of the following best describes the governing factor of conventional hydrogel permeability?

- A Conventional hydrogel permeability is linearly related to its water content
- B Conventional hydrogel permeability is logarithmically related to its water content
- C Conventional hydrogel permeability is closely related to its water content
- D Conventional hydrogel permeability is exponentially related to its water content

5 How do manufacturers increase the water content of most conventional hydrogels, compared with pHEMA?

- A By hydration in hypertonic solution
- B Using specialised surface treatments
- C By adding specific monomer types
- D Using silicone-based additives

6 Which of the following can act to reduce conventional hydrogel lens transmissibility?

- A Lens dehydration
- B Surface deposition
- C Pervaporation
- D Reducing centre thickness

7 Which of the following significantly affects the amount of oxygen reaching the corneal surface in soft lens wear?

- A Tear exchange with a blink
- B Changes in lens power
- C Lateral diffusion from well-supplied corneal regions to less well-supplied regions
- D Increasing inter-blink interval

8 Which of the following is TRUE?

- A The edge effect provides artificially high values of Dk and the boundary effect provides artificially high values of Dk
- B The edge effect provides artificially low values of Dk and the boundary effect provides artificially low values of Dk
- C The edge effect provides artificially high values of Dk and the boundary effect provides artificially low values of Dk
- D The edge effect provides artificially low values of Dk and the boundary effect provides artificially high values of Dk

9 Which if the following statements is true?

- A Silicone hydrogel materials offer greater transmissibility than conventional hydrogel materials
- B In silicone hydrogel materials, there is no oxygen transport through the water within the material
- C Silicone hydrogel materials are principally dependent on oxygen transport through the water within the material
- D Silicone hydrogel materials offer less dehydration than conventional hydrogel materials

10 The amount of oxygen reaching the corneal surface is:

- A Linearly related to lens transmissibility
- B Related to both lens transmissibility and the difference in oxygen tension between the front and back of the lens
- C Linearly related to the difference in oxygen tension between the front and back of the lens
- D Mainly a function of lens material dehydration

11 Dk/t is a good indicator of likely physiological performance for conventional hydrogels because:

- A Dk/t is a direct measure of the amount of oxygen reaching the corneal surface
- B At Dk/t < 30 units, there is an approximately linear relationship between Dk/t and the amount of oxygen which reaches the corneal surface
- C At Dk/t < 30 units, there is sufficient oxygen supply to prevent hypoxia in daily wear
- D For lenses with Dk/t < 30 units, physiological performance is similar

12 How much does a non-lens wearing cornea swell overnight?

- A About 4 per cent
- B About 1 per cent
- C About 8 per cent
- D About 15 per cent

There is one correct answer for each question. The deadline for response is March 4



Module C4836c To take part in this module online go to www.optometryonline.net and click onto the education section. Follow the links for OPTICIAN CET. Our CET is supported by Evolve. Online participation will allow participants to have an instant decision of success or the opportunity to repeat the exercise if unsuccessful. Alternatively, readers may still complete and submit the enclosed answer sheet as before should they not have internet access.